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Assessment of the Applicability of Existing Health and Welfare Criteria to General Aviation Aircraft Noise and to General Aviation Airport Communities

Science Applications, Inc.
McLean, VA

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FINAL REPORT

ASSESSMENT OF THE APPLICABILITY OF EXISTING HEALTH AND WELFARE CRITERIA TO GENERAL AVIATION AIRCRAFT NOISE AND TO GENERAL AVIATION AIRPORT COMMUNITIES

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Existing metrics of environmental noise and its impact on people are reviewed for their suitability in assessing the impact of general aviation (GA) noise on people in airport communities. GA aircraft consist of noncommercial aircraft in propellor-driven, jet, and helicopter categories. In a recent year over 124 million GA operations were performed at approximately 6,000 public-use airports. Available criteria (dose response relationships) are discussed in detail for various health effects of noise, focussing on individual and community annoyance responses, but also including noise-induced hearing loss, communication interference, sleep disturbance, and nonauditory physiological effects. It is concluded that there are only marginal differences in the way several noise metrics predict individual response; therefore, the simplest measurement (A-weighting without a duration correction) is recommended. For community response, no existing annoyance criteria may be entirely appliable to GA airport communities, based on results of several studies. For the time being the criteria developed by Schultz should be used. Information in appendices include a bibliography of health effects of aircraft noise; statistics on the mix of GA aircraft types, distribution of daily GA operations by airport types, and population density around GA airports; and GA flight procedures.

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1. INTRODUCTION

1. INTRODUCTION

1.1 Background

Since the introduction of the turbine powered jet aircraft into the commercial aviation fleet, considerable attention has been focused on the aviation noise impact upon surrounding airport communities. Increased public awareness of the effects of noise exposure and its adverse impact on the daily lives of individuals and communities has resulted in significant efforts aimed at controlling the level of environmental noise resulting from aircraft operations. Additionally, considerable effort has been devoted to the understanding of the relationships between the physical parameters of noise and human response.

Over the past two decades, research has led to the development of a number of methods which are purported to provide a high correlation between quantitative measures of noise and human response to this noise. A significant proportion of these research efforts have dealt with the effects of aircraft noise exposure. However, compared with the commercial jet aircraft, relatively little of this research has addressed general aviation (GA) noise and community noise impact around GA airports. It is unclear whether existing noise effects and dose-response relationships applicable to commercial jet aircraft are appropriate for predicting the impacts resulting from GA aircraft operations. Some of this uncertainty is based on a number of acoustic, demographic, and operational differences which distinguish GA and commercial aviation. For example, GA aircraft generally produce less intense noise levels than commercial jets and, they cover a wide range of aircraft types whose noise characteristics are very different from those of the larger jet aircraft. Also, GA aircraft typically operate from small airports surrounded by urban and residential communities whereas the larger airports serving commercial jet aircraft are usually located in more highly populated metropolitan areas. However, residential encroachment upon the airport facility may be more severe around GA airports.

Non-acoustic factors which have been found to influence noise response are likely to be different for the two types of airport communities. Due to differences in airport use requirements, airport configurations and facilities, and aircraft performance characteristics, the operational procedures and flight patterns used by GA aircraft at GA airports are not as well defined or controlled as those employed by commercial jets operating from larger airports. Because of these differences, a comprehensive assessment of the magnitude of GA noise and the consequent health and welfare impacts cannot be predicted with the same degree of confidence as that associated with commercial aircraft operations.

1.2 Purpose of Study

It has been estimated that in 1975, over 124 million GA operations were performed at approximately 6,000 public-use towered and non-towered airports in the United States. Because of this high level of air traffic activity, it is believed that GA aircraft operations may have a significant noise impact upon those communities surrounding airports which serve GA aircraft types. However, a comprehensive assessment of the magnitude of GA noise impact has never been made due to the uncertainties regarding human response to GA noise exposure, and the lack of data concerning key aircraft/airport parameters which influence the level of community noise exposure. Thus, the purpose of this study was to perform the following tasks relative to GA aircraft noise and its potential impact upon surrounding airport communities: 1) [redacted] 2) [redacted] The intent of [redacted] The choice of appropriate levels to protect public health and welfare will involve value judgments which concern political, social, ethical, and economic considerations which are clearly beyond the scope of this investigation.

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*The term criteria as used here refers to dose-response relationships between noise exposure and human response.

1.3 Report Overview

Section 2 of this report presents a general description of the noise characteristics of the three general categories of GA aircraft, i.e., small propeller-driven aircraft, jet (turbojet and turbofan) aircraft and helicopters.

Section 3 presents a detailed discussion of the existing health and welfare criteria related to the following noise effects categories:

- Individual and Community Response
- Communication Interference
- Noise-Induced Hearing Loss
- Sleep Disturbance
- Nonauditory Physiological Effects
- Behavioral and Performance Effects

A significant proportion of the discussion presented in Section 3 is devoted to laboratory and social survey investigations dealing with the adverse response of individuals and communities exposed to various types of noise sources. Attention has been focused on individual and community response because of the extensive research effort which has been directed toward quantifying subjective assessment of the various physical parameters associated with individual and cumulative noise exposure events. Section 3 also presents a discussion of the applicability of the existing health and welfare criteria relative to GA aircraft noise and to GA airport communities.

Appendix A contains a complete listing of the noise effects literature identified under the literature search requirement of this study effort.

Appendix B presents data related to GA aircraft/airport parameters which affect the extent of community noise impact. These data were obtained or developed from Federal Aviation Administration (FAA) publications presenting actual as well as projected aircraft/airport operations data and from the results of a comprehensive CY 1975 GA activity survey. The parameters presented in Appendix B include the following:

- Mix of GA aircraft types
- Level and distribution of daily operations (by airport type)
- Flight procedures
- Population distribution (or density) around airports

Based on these aircraft/airport parameters, Appendix B also presents an estimate of the noise impact upon GA airport communities resulting from GA aircraft operations. The impact estimate is quantified in terms of the number of people exposed to day-night sound levels of 55 dB or greater and, is applicable to CY 1975 GA aircraft operations.

2. GENERAL AVIATION (GA) AIRCRAFT TYPES AND NOISE CHARACTERISTICS

2. GENERAL AVIATION (GA) AIRCRAFT TYPES AND NOISE CHARACTERISTICS

GA aircraft can be separated into three general categories: propeller-driven, jet, and helicopter. The propeller-driven aircraft are powered by either reciprocating-piston or gas turbine engines. The major sources of noise include the propeller, engine, and engine exhaust. However, regardless of engine type, the propeller is almost always the dominant noise component. The propeller noise signature is comprised of a harmonic series of discrete frequency tones with the dominant fundamental tone typically in the range of from 50 to 250 Hz. Noise levels above the fundamental tone are produced by higher propeller harmonics and by discrete frequency and broadband noise from the engine and engine exhaust. A number of variables are known to influence the noise generated by propellers. The most significant of these variables are: 1) propeller tip speed relative to the airstream, 2) static air temperature, and 3) propeller design characteristics.

Jet aircraft can be separated into two general classes: turbojet and turbofan. Both aircraft types are powered by turbine engines which consist basically of a gas genertor, i.e., a compressor-burner-turbine combination, which provides a supply of "hot", high-pressure gases. The turbojet engines utilize this gas generator with an exhaust nozzle through which the hot gases are accelerated to provide the aircraft with forward thrust. In addition to the basic turbojet-engine components, the turbofan engine has a fan, a duct for "cold" air flow and an enlarged turbine to power the fan. There are two major sources of noise associated with both engine types, jet exhaust and turbo-machinery. The jet exhaust noise results from turbulent mixing of high velocity exhaust gases with the surrounding ambient air. Jet exhaust noise is broadband in nature with a significant proportion of acoustic energy concentrated in the low frequency bands. An advantage of turbofan engines over turbojets is the reduction of jet exhaust noise associated with the lower jet exhaust velocity. The intensity of jet exhaust noise has been shown to be proportional to the eighth power of the velocity of the jet exhaust relative to the ambient air. Therefore, small reductions in velocity may result in significant reductions in noise. Turbo-machinery noise is also broadband, but contains strong discrete high-frequency components or tones due to the rotating fan and/or compressor blades. For the turbojet engines, the dominant noise source is the jet exhaust, except at low engine power settings where the turbo-machinery noise is most detectable. For the turbofan engines, as the bypass ratio (the ratio of the "cold" air flow rate to the "hot" air flow rate) and the diameter of the fan increase, the fan noise can become the dominating noise.

Helicopters are powered by either reciprocating-piston or gas turbine engines. The principal noise sources are those associated with the main rotors or main and tail rotors, drive engine(s), and gearbox(es). All of these sources produce discrete frequency and broadband noise. Under certain conditions, helicopter rotors may generate impulsive noise, commonly referred to as "blade slap" or "banging." Blade slap noise is typically observed on most tandem rotor helicopters and may be generated by several types of single lifting rotor helicopters as well. For most helicopter types, the acoustic energy is concentrated in the frequency range below 1000 Hz. The frequency structure and temporal variation of the sound can vary extensively, from noises which are dominated by low frequency rotor harmonics (described as beating or rumbling) to noises which are dominated by the higher harmonics (described as slapping or banging).

Figures 2-1, 2-2, and 2-3 show typical acoustic spectra for each of the three GA aircraft types. Table 2-1 presents information to identify the spectra shown in Figures 2-1, 2-2, and 2-3 including: 1) aircraft type, 2) maximum gross weight, 3) type and number of engines, 4) maximum horsepower or thrust per engine, and 5) flight mode, i.e., takeoff, landing, or flyover.

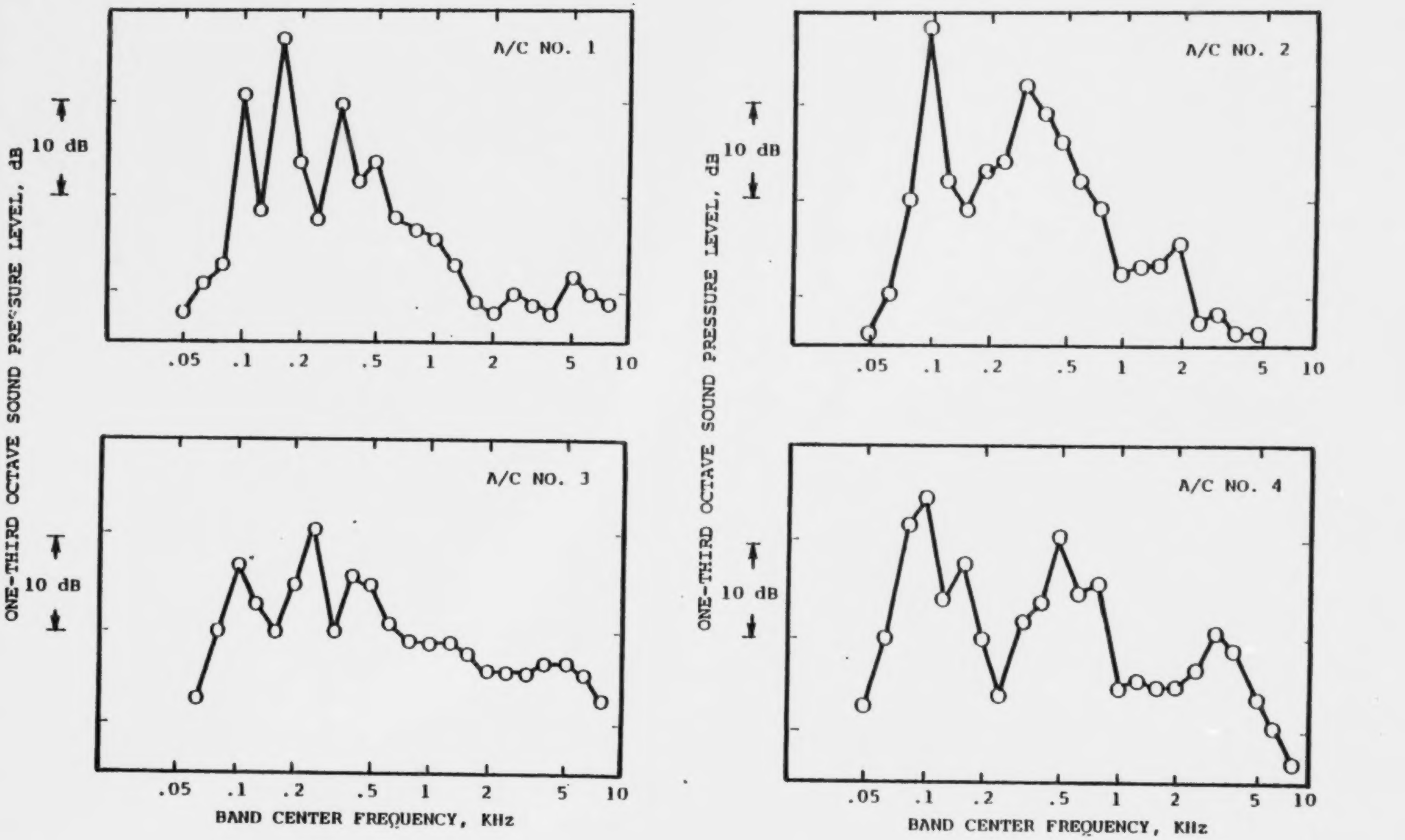

FIGURE 2-1. TYPICAL ACOUSTIC SPECTRA FOR PROPELLER-DRIVEN (GA) AIRCRAFT

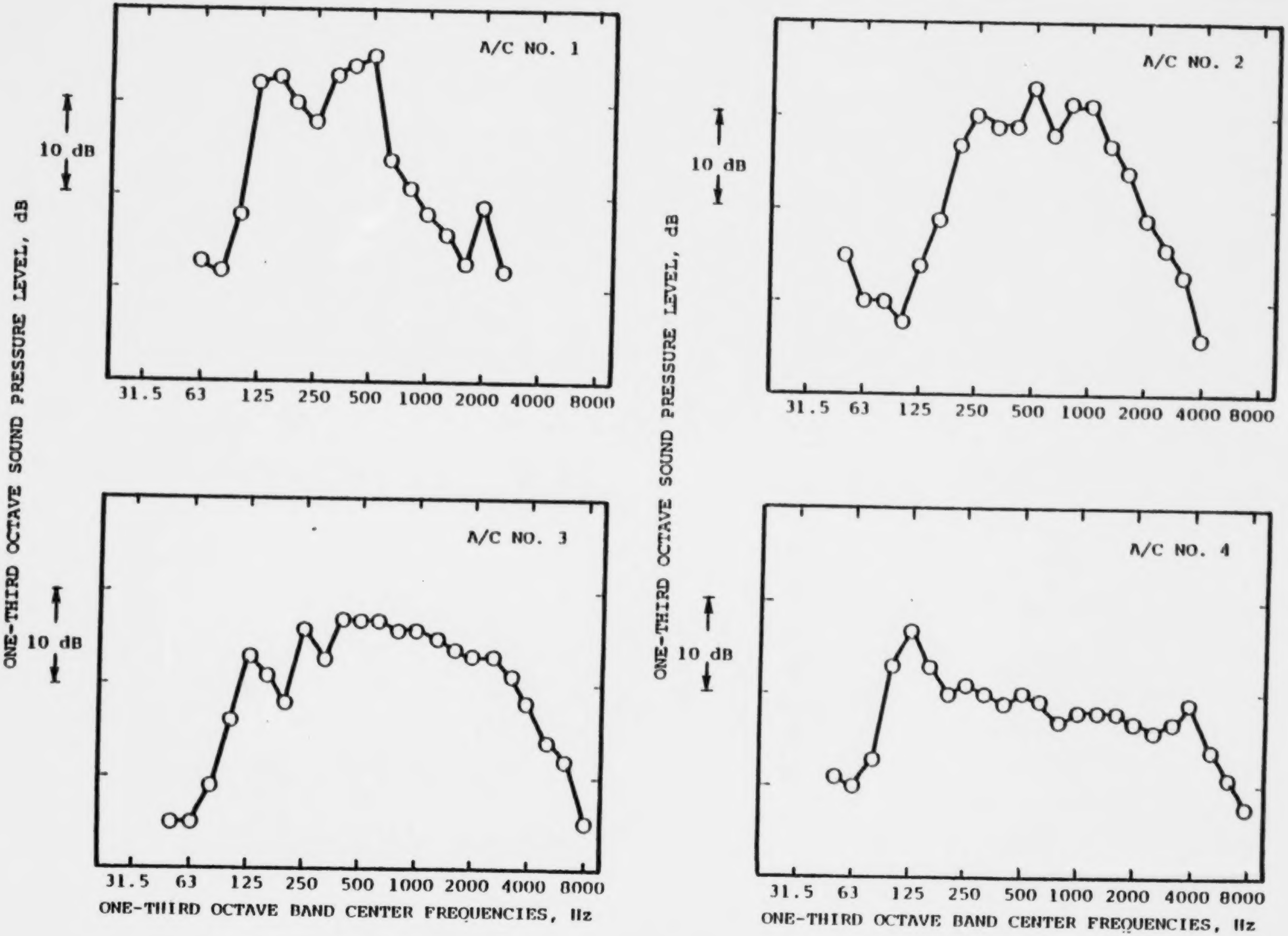

FIGURE 2-2. TYPICAL ACOUSTIC SPECTRA FOR TURBOJET (GA) AIRCRAFT

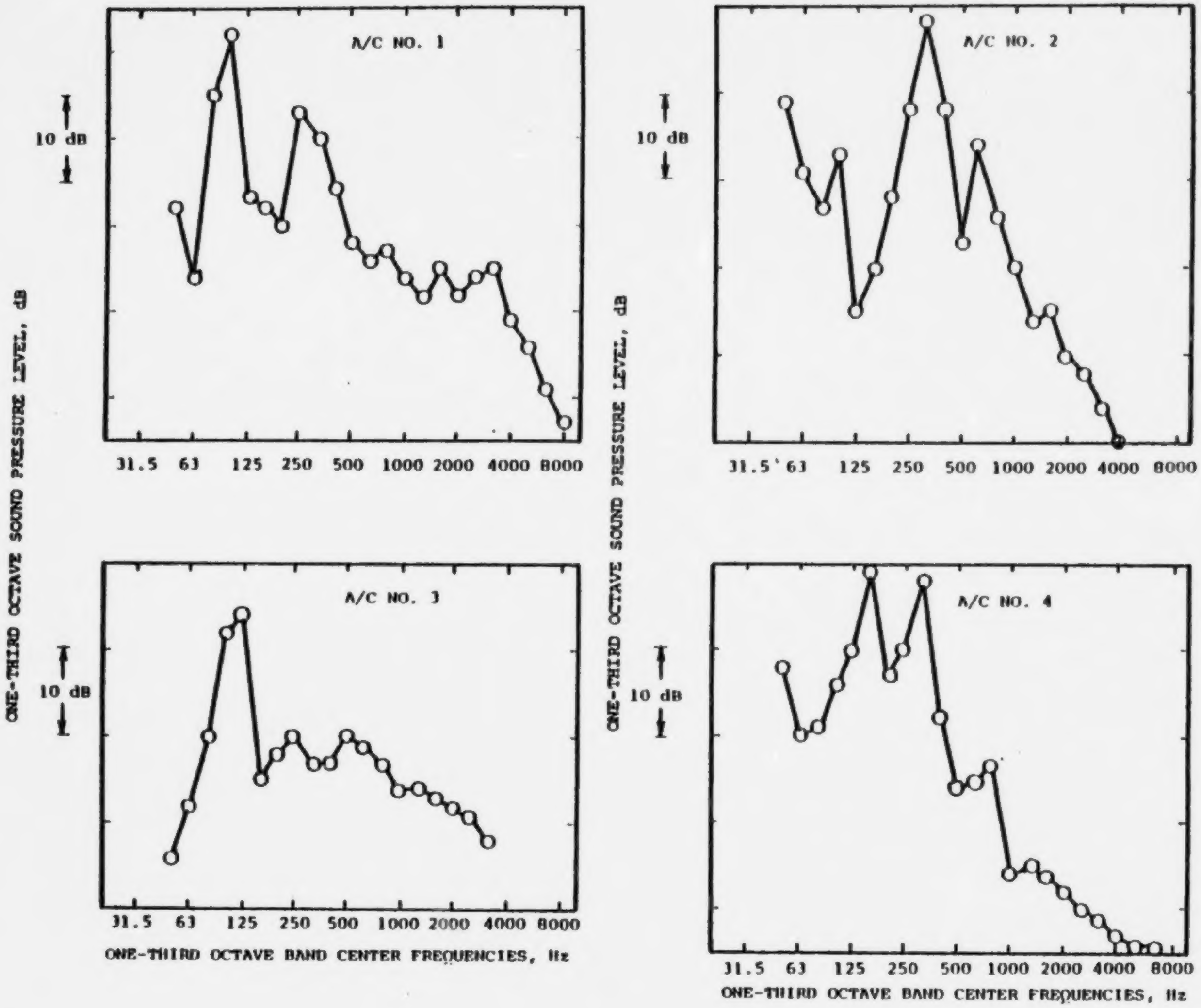

Figure 2-3. TYPICAL ACOUSTICAL SPECTRA FOR HELICOPTER (GA) AIRCRAFT

Table 2-1 Identification of Spectra for GA Aircraft Types Shown in Figures 2-1, 2-2, and 2-3

	AIRCRAFT IDENTIFICATION			PROPULSION SYSTEM			
FIGURE NUMBER	AIRCRAFT (A/C) NUMBER	TYPE	MAX. GROSS WT. Lbs.	ENGINE TYPE	NO. OF ENGINES	MAX H.P. (THRUST-Lbs.) PER ENGINE	FLIGHT MODE
2-1	1	PD	3,400	Piston	1	295	Flyover
	2	PD	6,100	Turbine	1	575*	Flyover
	3	PD	5,700	Piston	2	260	Flyover
	4	PD	5,200	Piston	2	250	Takeoff
2-2	1	TJ	12,500	Turbine	2	(2,850)	Takeoff
	2	TJ	20,500	Turbine	2	(3,360)	Takeoff
	3	TJ	12,500	Turbine	2	(2,850)	Landing
	4	TJ	20,500	Turbine	2	(3,360)	Landing
2-3	1	H	2,050	Piston	1	190	Flyover
	2	H	3,000	Turbine	1	317*	Flyover
	3	H	18,500	Turbine	2	1,400*	Flyover
	4	H	33,000	Turbine	2	2,850	Flyover

PD - Propeller Driven
TJ - Turbojet
H - Helicopter

* Shaft Horsepower

Table 2-2 presents a listing of the expected sound levels generated by typical GA and commercial transport aircraft operating at a source-receiver separation distance of approximately 1,000 feet. The sound levels shown on Table 2-2 are given in terms of Effective Perceived Noise Level (L_{EPN}) and were obtained from published data presented in References 1,2, and 3. For the GA and commercial transport aircraft categories, Table 2-2 identifies the following: 1) aircraft type, 2) typical operational gross weight (depending on flight mode), 3) type and number of engines, 4) horsepower or thrust per engine associated with the reported sound level and, 5) flight mode.

Table 2-2 Sound Levels for Typical General Aviation and Commercial Transport Aircraft Operating at a Source-Receiver Distance of Approximately 1000 Feet

AIRCRAFT IDENTIFICATION			PROPULSION SYSTEM				
CATEGORY	TYPE	TYPICAL GROSS WT (lbs)	ENGINE TYPE	NO. OF ENGINES	HORSEPOWER (THRUST-lbs) PER ENGINE	FLIGHT MODE	EFFECTIVE PERCEIVED NOISE LEVEL, (L_{EPN}), dB
General Aviation	PD	2,750	Piston	1	200	Flyover	82.2
	PD	3,800	Piston	1	310	Flyover	87.3
	PD	6,100	Piston	2	301	Flyover	90.2
	PD	12,500	Piston	2	750*	Flyover	88.0
	TJ	13,500	Turbine	2	(2,500)	Takeoff	118.9
	TJ	20,372	Turbine	2	(2,800)	Takeoff	115.2
	TF	11,650	Turbine	2	(1,550)	Takeoff	88.7
	TF	18,000	Turbine	2	(2,630)	Takeoff	98.5
	H	1,900	Piston	1	190	Flyover	76.0
	H	2,950	Piston	1	305	Flyover	84.1
	H	5,590	Turbine	1	1,050*	Flyover	83.9
	H	5,400	Turbine	2	420*	Flyover	88.2
Commercial Transport	TF	116,000	Turb. (LBPR)	2	(12,000)	Takeoff	109.8
	TF	82,000	Turb. (LBPR)	2	(4,000)	Approach	91.0
	TF	191,000	Turb. (LBPR)	3	(12,000)	Takeoff	112.6
	TF	123,000	Turb. (LBPR)	3	(4,000)	Approach	94.4
	TF	336,000	Turb. (LBPR)	4	(15,000)	Takeoff	115.6
	TF	198,000	Turb. (LBPR)	4	(6,000)	Approach	106.5
	TF	440,000	Turb. (HBPR)	3	(41,000)	Takeoff	102.1
	TF	290,000	Turb. (HBPR)	3	----	Approach	95.6
	TF	713,000	Turb. (HBPR)	4	(45,000)	Takeoff	114.1
	TF	450,000	Turb. (HBPR)	4	----	Approach	103.9

PD - Propeller Driven
TJ - Turbojet
TF - Turbofan
H - Helicopter
LBPR - Low By-Pass Ratio
HBPR - High By-Pass Ratio
* - Shaft Horsepower

3. IDENTIFICATION AND EVALUATION OF EXISTING HEALTH AND WELFARE CRITERIA

3. IDENTIFICATION AND EVALUATION OF EXISTING HEALTH AND WELFARE CRITERIA

3.1 Individual and Community Response

A number of rating measures* have been proposed for quantifying the subjective effects of noise on people. However, all of these measures can be separated into two general categories: single-event and multiple-event measures. The single-event measures attempt to describe how humans judge or perceive the particular physical parameters of an individual noise exposure in terms of attributes such as loudness, noisiness, annoyance, etc. Multiple-event measures on the other hand attempt to describe how people perceive or are affected by cumulative noise exposure over a specified period of time. Multiple-event measures are usually based on single-event measures and may consider (implicitly or explicitly) other acoustic and non-acoustic factors such as the temporal distribution of the noise events, ambient noise level, number of individual noise events, season, attitudes of those people exposed to the noise, etc..

In order to assess the impact of aircraft noise upon GA airport communities, the quantitative measures of the noise exposure must be scaled in terms of their effects on people. It is essential that the dose-response criteria used in the noise impact assessment represent the highest possible correlation between the noise exposure and the consequent effects. The following sections discuss the noise measures currently used to quantify these effects as well as the validity and accuracy of these measures relative to the noise characteristics of GA aircraft.

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*Due to a lack of standardization in terminology, these measures are sometimes referred to as scales, procedures, schemes, indices, descriptors, etc.

3.1.1 Subjective Response Measures to Single Events

3.1.1.1 Psychoacoustic Testing

Single-event measures currently used to quantify humans' subjective perceptions of noise have been developed from theoretical concepts concerning the auditory mechanism and from empirical relationships derived from extensive psychoacoustic research performed over the past 40 years. A significant proportion of this psychoacoustic research has been devoted to understanding and predicting human response to aircraft noise. Historically, two psychoacoustic research methods have been employed in the investigation of aircraft noise: laboratory and field studies.* Using various psychophysical methods, objective measures along with judged assessments of the noise are obtained from single noise exposure events. These data are then used to assess subjective response to the physical characteristics of the noise such as intensity, spectral distribution, duration, etc., or to develop human response scales, typically in terms of loudness, noisiness, annoyance, or acceptability, as a function noise level.

A number of psychophysical methods have been used in laboratory investigations. These methods are:

- Method of Constant Stimuli (paried comparisons)
- Method of Adjustment
- Magnitude Estimation
- Category Scaling

These methods are adequately defined in the open literature (e.g., Reference 4) and will not be discussed here. The psychophysical methods used in field study investigations are limited to paired comparisons, magnitude estimation, and category scaling since they employ actual noise sources for test and reference sounds.

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*Field studies are not to be confused with social survey study methods used to quantify community response to noise exposure.

Psychoacoustic investigations conducted in a laboratory environment are generally performed using one of the following listening conditions: semi-reverberant, free-field, or earphones. Test and reference sounds studied include real (recorded) or synthesized aircraft noise, recorded or synthesized sounds such as tones, bands of noise and other stationary or time-varying spectral signatures. Field studies on the other hand are generally limited to indoor or outdoor test environments using actual noise sources (as compared to recorded noise sources) for test and reference sounds. Because of the extreme variability among psychoacoustic testing procedures, a few studies have been performed to investigate the comparative reliability and accuracy of some of the psychophysical methods and listening conditions utilized (Clark and Kryter[5,6], and Mabry and Parry[7]). Using ten different noises (a standard and nine comparison noises), Clark and Kryter[5,6] concluded that test results obtained using any of the three listening conditions were equivalent. In a separate study comparing the magnitude estimation technique and the method of paired comparisons, Clark and Kryter[6] found that both methods gave approximately the same estimates of the points of subjective equality for the noise pairs, and both showed similar correspondence to predictive physical measures. Mabry and Parry[7] found that the method of magnitude estimation was better than the other three psychophysical procedures when more complex measures such as L_{EPN} are involved. Additionally, they presented data which suggest that the type of standard or reference sound used as a comparison noise may influence subjective response markedly.

Based on the results of an investigation comparing various methods used for predicting the loudness and acceptbility of noise, Scharf et al.[8] found that the attribute being evaluated (e.g., annoyance vs. loudness) does not appreciably influence the predictability of the psychophysical procedure, although listeners appear to be able to differentiate between these responses (e.g., Berglund et al.[9,10]). Also, Scharf et al.[8] concluded that there appears to be little difference between the reverberant (diffuse-field) and free-field test environments but that, test results obtained using earphones showed greater variability in predictiveness.

3.1.1.2 Types of Single-Event Measures

Subjective response to single events is typically estimated using two general methods: measuring frequency-weighted sound levels and calculating various measures such as loudness level and perceived noise level. Other measures are based on or are variants of one of these two methods.* Both measurement methods employ energy summation procedures which vary only in terms of the emphasis placed on the response to certain audible frequency bands and in degree of computational complexity. The simplest summation procedure is the frequency-weighted sound pressure level technique. The four frequency-weighting procedures which have been standardized and incorporated into commercial sound level meters are the A(L_A), B(L_B), C(L_C) and D(L_D) networks. Although it is not yet standardized, an E-weighting network (L_E) is also in use. These networks are based on empirical relationships derived from psychoacoustic testing. The relative one-third octave band weightings for each of these networks are shown in Table 3-1.

The summation procedures associated with the loudness level measures are considerably more complex than the frequency-weighted sound pressure level procedures. These include Zwicker's Loudness Level (LL_Z), and Stevens's Loudness Level (LL_S) (computed using either Stevens's Mark VI (MK VI) or Mark VII (MK VII) calculation procedures).

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*Although the auditory attribute purported to be measured by each method may be different, both relate the physical properties of the sound to a subjective or a perceived auditory experience. Whether or not the perceived auditory experience actually differs, depending on the physical parameter of the sound investigated and the label assigned to it (i.e., loudness, noisiness, acceptability, intrusiveness, annoyance, and so on) has been the subject of controversy among researchers over the past several years (e.g., Kerrick et al.[11], Stevens,[12] Scharf et al.[8], and Berglund et al.[9,10]).

Table 3-1 One-Third Octave Band Frequency Weightings for the A, B, C, D and E Networks

LOWER AND UPPER CUT-OFF FREQUENCY	BAND CENTER FREQUENCY	BAND WEIGHTINGS, dB				
		A	B	C	D	E
(45-56)	50	-30.2	-11.6	-1.3	-12.5	-17.4
(56-71)	63	-26.2	- 9.3	-0.8	-11.0	-14.5
(71-90)	80	-22.5	- 7.4	-0.5	- 9.0	-11.8
(90-112)	100	-19.1	- 5.6	-0.3	- 7.5	- 9.4
(112-140)	125	-16.1	- 4.2	-0.2	- 6.0	- 7.3
(140-180)	160	-13.4	- 3.0	-0.1	- 4.5	- 5.3
(180-224)	200	-10.9	- 2.0	-0.0	- 3.0	- 3.6
(224-280)	250	- 8.6	- 1.3	0.0	- 2.0	- 2.2
(280-355)	315	- 6.6	- 0.8	0.0	- 1.0	- 1.1
(355-450)	400	- 4.8	- 0.5	0.0	- 0.5	- 0.3
(450-560)	500	- 3.2	- 0.3	0.0	0.0	0.1
(560-710)	630	- 1.9	- 0.1	0.0	0.0	0.1
(710-800)	800	- 0.8	0.0	0.0	0.0	0.0
(900-1120)	1000	0.0	0.0	0.0	0.0	0.0
(1120-1400)	1250	+ 0.6	0.0	0.0	+ 2.0	+ 0.7
(1400-1800)	1600	+ 1.0	0.0	-0.1	+ 5.5	+ 2.1
(1800-2240)	2000	+ 1.2	- 0.1	-0.2	+ 8.0	+ 4.0
(2240-2800)	2500	+ 1.3	- 0.2	-0.3	+10.0	+ 5.9
(2800-3550)	3150	+ 1.2	- 0.4	-0.5	+11.0	+ 7.6
(3550-4500)	4000	+ 1.0	- 0.7	-0.8	+11.0	+ 8.7
(4500-5600)	5000	+ 0.5	- 1.2	-1.3	+10.0	+ 9.1
(5600-7100)	6300	- 0.1	- 1.9	-2.0	+ 8.5	+ 8.3
(7100-9000)	8000	- 1.1	- 2.9	-3.0	+ 6.0	+ 6.5
(9000-11,020)	10,000	- 2.5	- 4.3	-4.4	+ 3.0	+ 3.8

Both Stevens's MK VI and Zwicker's procedures have been internationally standardized. These calculation methods for computing loudness level all take into account the masking effects of lower frequency bands of noise which inhibit the contribution to loudness of relatively higher frequency bands. However, there are a number of differences between Zwicker's method and those of Stevens's. These differences are:

1. Zwicker's method is considerably more complex than Stevens's methods;
2. Zwicker's method is based more firmly on theory and can be applied to more complex noise spectra;
3. Unlike Stevens's methods, Zwicker's method takes into account the well-known asymmetry in masking, i.e., an upward spread of masking of higher frequencies by lower frequencies.

Because of these differences, Zwicker's calculation procedure results in loudness level values which are typically 5 dB greater than those determined using Stevens's methods for the same noises.

Ollerhead[13] has discussed some of the similarities and differences between the basic frequency-weighted sound level and loudness level computation methods which have formed the basis for a multitude of subsequent variations. Ollerhead concludes that although the basic algebraic techniques in the two methods are very different, the net results show far more similarities than differences, particularly if attention is focused on the levels and spectra which are characteristic of aircraft noise. The main differences betweeen the frequency-weighted sound level and the loudness level procedures and their subsequent variations lie in the different frequency weighting functions.

Another computational scheme in general use is the Perceived Noise Level (L_{PN}). This procedure was based on the concept that perceived noisiness and perceived loudness were two distinct attributes of auditory experience.[14] However, as pointed out by Schultz[15], the original form of the procedure for calculating the perceived noise level of a broadband noise spectrum is basically the same as that of Stevens's MK VI procedure for calculating loudness level, with two exceptions: (1) the octave band levels used for evaluating an aircraft flyover are the maximum values attained in each band during the event, regardless of whether these peaks occur simultaneously; and (2) instead of assigning a loudness index to each measured frequency band level of noise (as in the MK VI calculation to represent its contribution to total loudness), a corresponding contribution to total perceived noisiness is assigned for each band. The summation equation used to arrive at the total perceived noisiness in noys* is identical to that used to calculate total loudness in sones for the MK VI procedure. Also, the equations used to convert from noys to perceived noise level and to convert from sones to loudness level (in phons) are identical.

Since its original development, the procedure for calculating perceived noise level has undergone a number of revisions, refinements and extensions which account for temporal and spectral complexities. These changes have purportedly improved correlation between objective and subjective measures of aircraft noise.

3.1.1.3 Factors Affecting Single-Event Measures

For the past two decades, psychoacoustic research in the field of subjective response to aircraft noise has been extensive. It is a difficult, if not an impossible task to identify all of the related investigations which have addressed the subject area over this time period. Most of the work has been focused on improving objective measures of an individual's subjective or judged assessment of the physical characteristics of jet aircraft noise. Included in this research have been investigations of audible pure tones, temporal patterns of aircraft flyover noise signals (simulated and actual recordings), signal duration, combination effects of pure tones and duration, and the effects of Doppler shift.** Additionally, investigations into the effects of background noise and the growth of the perceived magnitude as a function of stimulus level have been conducted. Research in other areas particularly relevant to GA aircraft have also been performed. These areas include revision to the shape of the noy contours at low frequencies and the perceived magnitude of impulse noise signatures.

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*The unit of perceived noisiness is the noy, and values are read from tables or contours of equal perceived noisiness.

**Doppler shift is the apparent upward shift in frequency of a sound as a noise source approaches the listener, or the apparent downward shift when the noise source recedes.

Comprehensive reviews of earlier research studies which have contributed significantly to, or contain relevant comment upon, the development of widely used single-event noise measures are presented by Ollerhead,[13] Galloway,[16] and Schultz.[15,17] Therefore, the following sections will present only a summary of this development and will highlight some of the most important issues.

A. Duration and Tone Effects

After the introduction of the turbine powered jet aircraft into the commercial aviation fleet, it was observed that at the same overall sound pressure level, the noise produced by jet aircraft was perceived differently from that generated by the commercial propeller-driven (piston) aircraft.[14] This difference was purportedly due to the increased sensitivity of the human auditory system to higher frequency content of the jet aircraft noise signatures. This finding led to the development of the L_{PN} concept and the notion that noisiness and loudness are different auditory experiences. Subsequent research suggested that the L_{PN} procedure did not adequately account for the effects of signal duration or pure tone components.

A.1 Duration Effects

Kryter and Pearsons[18] found that for sounds that varied in duration over a range of 1.5 to 12 seconds, judged equivalent perceived noise level (as compared with a reference sound with constant sound level) increased by approximately 4.5 dB each time the duration was doubled. Pearsons[19] reported in a later study using longer periods of duration (up to 64 seconds) that the effect of duration on perceived noisiness is a continuously varying function of level. It was found that judged equivalent perceived noisiness corresponded to 6 dB per doubling of the signal duration in the range of 1.5 to 4 seconds, 3.5 per doubling between 4 and 16 seconds, and 2 dB per doubling for durations in excess of 16 seconds. Over the range of durations examined, 1.5 to 64 seconds, the perceived noise level increased by an average of 2.5 dB for a doubling of duration,* compared to the increase of 4.5 dB for a doubling of duration found in the previous tests. Williams et al.[20,21] found that for two aircraft flyovers with the same peak level but with different durations, the flyover having the shorter duration (10 dB-down duration measured from peak level) is judged to be more acceptable. Furthermore, it was reported that if two flyovers differ in duration by a factor of two, the peak noise level of the one having the longer duration must be 2.5 to 4.0 dB less than that of the other flyover, if the two are to be judged equally acceptable. This finding is in general agreement with the results reported by Pearsons.[19] As shown in Figure 3-1, changes in signal duration by a factor of 2 appear to follow an approximate 3 dB trading relationship for other acceptability rating categories as well, i.e., barely acceptable and unacceptable.

In a study by Little and Mabry[22] it was reported that sounds with durations between 1 and 16 seconds did increase annoyance, but that the duration effect was always greater when subjects were instructed to attend to the duration of the sound and that the magnitude of the increase depended upon the test method. Also, it was reported that the penalty for doubling duration ranged from 2.1 to 3.1 dB when subjects were instructed to attend to duration compared to 0.6 to 1.9 dB when they were not.

Parry and Parry[23] contend that only when subjects are specifically directed to attend to duration is a duration effect observed and that when subjects attend to duration, they are actually rating the intensity of a sound in terms of its duration. It was pointed out that duration effects can also be observed in loudness judgments, contrary to the concept that duration is an inherent factor in noisiness judgments alone.

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*This is approximately equal to a doubling of acoustic energy, i.e., 3 dB per doubling of duration.

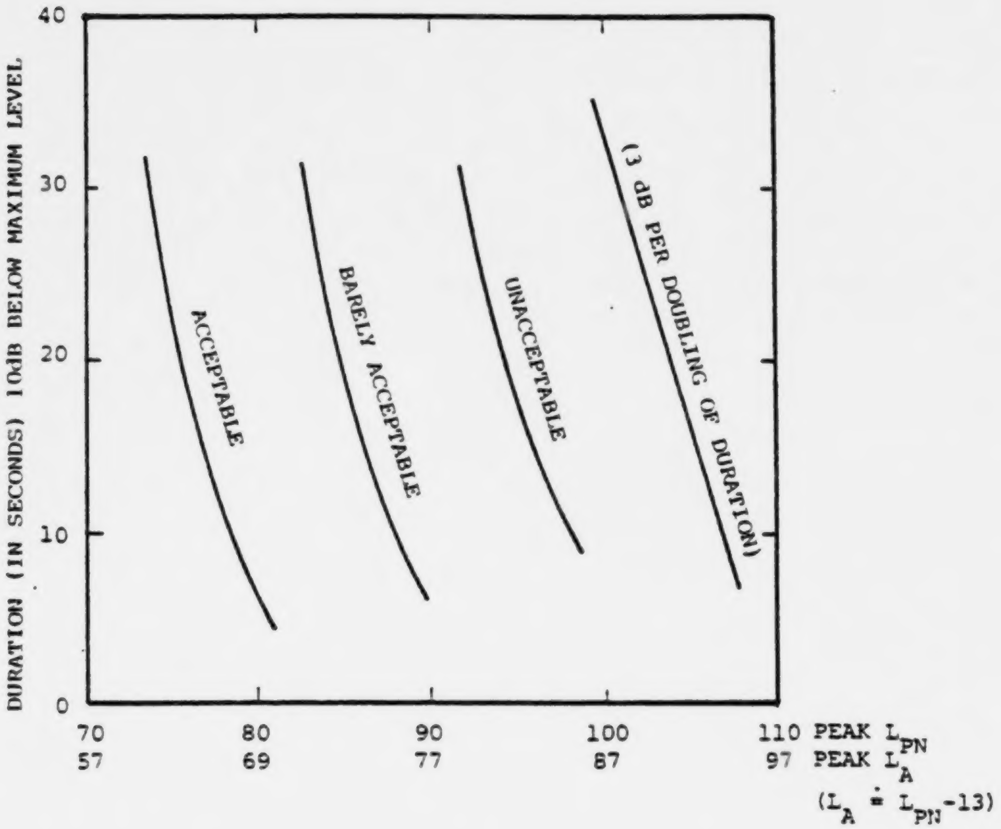

Figure 3-1. CONTOURS OF EQUAL NOISINESS BASED ON JUDGMENTS OF ACCEPTABILITY OF AIRCRAFT NOISES HAVING DIFFERENT DURATIONS (from Williams, et al., Reference 20).

In a study by Ollerhead[13] in which the perceived level of flyover noise produced by several aircraft categories was investigated, it was concluded that, based on the assumption of uniform duration/ perceived level tradeoff allowance, the application of a 3 dB per duration doubling improves the performance of the single-event measures and is close to the optimum for all aircraft categories considered (jet aircraft, propeller-driven aircraft and helicopters).

A.2 Effects of Pure Tones

Several investigations have been performed to assess the effects of pure tones on subjective response and to evaluate the various correction procedures used to account for the increased sensitivity of humans to signals containing discrete frequency components (e.g., Ollerhead,[13,24,25] Kryter and Pearsons,[18] Pearsons,[26] Pearsons et al.,[27] Adcock and Ollerhead,[28] and Pearsons and Bennett[29]). The general conclusion reported by these studies was that the presence of discrete frequencies, or pure tones, influences the perceived "noisiness" of acoustic signals. It was found that correction for the presence of pure tones improves the correlation between the objective measurement and the subjective assessment of the noise signals.

A.3 Combination Effects of Duration and Pure Tones

A number of studies have investigated the effects of combining duration and pure tone corrections on the subjective assessment of aircraft noise (e.g., Pearsons,[26] Pearsons and Bennett,[29] Adcock and Ollerhead,[28] and Kryter et al.[30]). Results from these studies indicate that objective measures which incorporate tone and duration corrections provide better agreement with subjective judgements of acceptability than do the other measures which do not. However, most of these studies also concluded that the more complex tone and duration corrected measures and some of the simpler measures such as L_A and L_D were not significantly different in terms of their ability to predict subjective response.

B. Other Effects

Other effects on perceived noisiness of aircraft flyovers which have been investigated include Doppler shift and background noise. An investigation by Ollerhead[25] reported that flyover noises with a pronounced Doppler shift (i.e., actual flyovers) required less correction for duration than noises without Doppler shift (i.e., simulated flyovers).

In a later study by Pearsons et al.[31] it was concluded that L_{EPN}, with the 3 dB increase in judged magnitude per doubling of duration was an accurate predictor of the noisiness of aircraft flyovers containing Doppler shift. However, at altitudes of 500 feet or less and nominal speed of 200 mph, the L_{EPN} procedure somewhat underestimated the apparent noisiness by approximately 2.5 to 3.5 dB.

Rosinger et al.[32] investigated the response judgments of annoyance to approaching and receding sounds which continuously increased or decreased in intensity and/or frequency. It was reported that a continuous increase in noise frequency and intensity as the source appears to approach the observer is perceived to be more annoying than when it appears to be moving away from the observer in spite of the fact that the duration and total energy of both signals were identical (within tolerances).

A number of studies have reported the results of investigations to determine the effects of background or ambient noise on the subjective assessment of aircraft noise exposure (e.g., Pearsons,[19] Powell and Rice,[33] Bottom,[34] Sternfeld et al.,[35] and Bottom and Waters[36]).
Using three background noise levels (L_{PN} of 47, 64, and 80 dB) with a peak frequency of 250 Hz, Pearsons[19] concluded that background noise can reduce the judged noisiness of an aircraft flyover. However, to obtain a 4 to 5 dB reduction in judged perceived noisiness, background noise must be increased by 33 dB. For example, a mean rating of "Noisy" was approximately 92 dB with background noise of 47 dB, while the mean rating of "Noisy" was approximately 97 dB with background noise of 80 dB. Using road traffic background noise, Powell and Rice[33] report a decrease in subjective

response of approximately 4.5 dB (A-weighted sound level) to individual aircraft noises ranging from 45.9 dB to 64.8 dB as the background noise levels increased from a mean level of 32.3 dB to 46.4 dB. It should be noted that the effects of background noise reported by Pearsons[19] and Powell and Rice[33] were obtained with the background noise remaining constant over each test session. Powell and Rice[33] report that when the background levels were changed between each aircraft noise flyover, no consistent or significant effects were noted.

3.1.1.4 Comparison of Single-Event Measures Used to Assess Individual Response to Aircraft Noise

A review of several earlier studies investigating subjective response to aircraft noise or, acoustic signals similar to aircraft noise, has produced some conflicting results regarding the choice of the optimum single-event measure. A number of these studies have emphasized the importance of signal duration and discrete frequency content in subjective assessment of the noise event. Some of the measures investigated considered only the maximum amplitude of the sound level produced while others accounted for amplitude variation over a specified time interval of the event. Almost all of these measures considered the frequency distribution of the sound, either explicitly and implicitly.

The choice of the single-event measure providing the best objective measure of the subjective assessment of aircraft noise has tended to vary from study to study. A number of factors have, most likely, contributed to the variability in the reported study results. Some of these factors include:

- Type of sound studied
- Type of reference sound
- Comparison method (psychophysical procedure)
- Listening conditions
- Number of subjects
- Dynamic range of sound levels judged
- Spectral and temporal characteristics of the sounds
- Method used to evaluate test results
- Subject differences

Although earlier psychoacoustic research investigations have provided an extensive data base, methodological differences among these investigations preclude a comprehensive assessment of the relative influence of each of the factors listed above. However, several studies have been performed in an attempt to assess the differences (or similarities) among the numerous single-event measures (e.g., Young and Peterson,[37] Schultz,[15,17] Botsford,[38] and Scharf et al.[8]). Using various comparison techniques, these studies evaluated the performance of objective measures of noise in terms of their ability to predict subjective response, or in terms of their correlation with other objective measures. The majority of these studies have reported that the more complex measures such as LL_Z, LL_S, and L_{EPN}, are superior to the simplier frequency-weighted sound level measures. However, a review of a number of these studies suggests that, although the more complex measures appear to correlate better with human response, they are only marginally better than some of the simplier measures (particularly L_A, L_D and L_E) and, in most cases, the differences between them are well within the range of measurement and computational error.

3.1.2 Individual Response to Aircraft Noise

3.1.2.1 Earlier Investigations

Relatively few of the earlier psychoacoustic research investigations were concerned with subjective response to noise produced by GA aircraft. Because the noise characteristics of propeller-driven aircraft and helicopters are very different from those of the larger commercial jets, it is not clear whether existing single-event measures are applicable to all GA aircraft types. In order to evaluate their applicability, two earlier investigations specifically addressing response to GA aircraft have been reviewed. Although several other aircraft noise investigations included GA aircraft, the results were not reported with respect to individual aircraft categories. Therefore, conclusions specifically related to GA aircraft could not be derived from the report findings.

In 1968, Ollerhead[25] conducted a paired comparisons test to study the subjective response to noise produced by GA aircraft. The primary objective was to determine the applicability of the perceived noise level concept in rating the relative noisiness of five representative GA aircraft types. These aircraft types are shown in Table 3-2. Other aircraft types evaluated included a Douglas DC-9-30 and a Boeing 707-120B.

In the main experiment, 28 subjects rated 35 recorded flyover sounds produced by the seven aircraft types (five GA and two commercial transports).* Subjects were instructed to evaluate the relative "noisiness" of two acoustic signals presented in pairs. The experiment was conducted in an anechoic environment (progressive wave chamber). The Standard Reference Sound (SRS) was an octave band of pink noise (i.e., random noise with a uniform spectrum level as measured by a constant percentage bandwidth analysis) centered on 1000 Hz with a duration of four seconds. Intermediate reference sounds with durations ranging from 4 to 32 seconds were constructed from shaped wideband noise spectrum which simulated jet exhaust noise. An "absolute" judged equivalent level was determined for each sound by direct and indirect comparison with the SRS. Levels of various single-event measures were then determined from sounds judged equivalent to the SRS.

Twenty-six single-event measures were evaluated by calculating the product-moment coefficient of correlation between the calculated and judged levels. Of the currently used single-event measures, it was reported that L_{PN}, with and without a tone correction, LL_Z, and L_D gave the best correlation with the subjective noise evaluation results. For the GA aircraft noise signals investigated, Ollerhead[25] reported that a duration correction** appeared to have little influence on the subjective noisiness of flyover sounds. By comparing the results to those from a number of simulated flyover sounds, Ollerhead[25] concluded that this could be explained by the influence of the Doppler frequency shift.

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*Fifteen of these sounds were synthesized from actual recordings of the three Piper aircraft to obtain various signal durations.

**Duration correction was defined by : $\Delta dB = 10 \log_{10} (T_{10}/15)$ where ΔdB is an increment to be added to the peak value of the single-event measure and T_{10} is the time interval between the 10 dB-down points in the single-event time history of the noise signal.

Table 3-2 GA Aircraft Types Used in Noise Response Study Described in Reference 25 (Ollerhead)

AIRCRAFT TYPE/MODEL	CLASSIFICATION	GROSS WT. (Lbs.)	INSTALLED H.P./THRUST (Lbs.)
Piper Cherokee 140	Single Piston Engine, 4-Place Sport/Business Aircraft	2150	150 H.P.
Piper Cherokee 6	Single Piston Engine, 6-Place Utility Aircraft	3400	260 H.P.
Piper Aztec	Twin-Piston Engine, 6-Place Executive Transport	5200	500 H.P.
Turbo-Commander	Twin Turboprop, 7-9 Seat Executive Transport	8950	1300 S.H.P.
Lear Model 23	Twin Turbojet, 8-Seat Executive Transport	12,500	5700 lbs.

Several points should be mentioned regarding Ollerhead's evaluation technique and basic findings. First, aircraft other than GA types were included in the overall assessment of the study results, i.e., a DC-9-30 and a 707-120B. Second, of the 35 aircraft flyover signals investigated, 20 represented actual aircraft flyovers while 15 were synthesized or "shaped signals" constructed from actual recordings of aircraft flyovers. Although the synthesized recordings sounded like aircraft flyovers, there was no change in frequency as the sound pressure level amplitude varied over the signal duration, a characteristic of an approaching and receding sound with pronounced frequency components. Finally, the method of evaluation used to evaluate the relative performance of the various single-event measures and to conclude that a duration correction does not influence subjective assessment of a flyover sound did not consider the accuracy* of the objective measures investigated.

Using the study results reported by Ollerhead,[25] the subjective response data have been divided into two aircraft categories, propeller-driven aircraft and jet (turbojet and turbofan) aircraft. For both of these aircraft categories, a "rank" ordering analysis of the relative performance of the currently used single-event measures was performed. The rank ordering was performed with respect to both average difference (accuracy) and variability (consistency) between the calculated and judged sound levels. The variability is specified in terms of the standard deviation about the mean. Table 3-3 presents the results of the rank ordering analyses. It may be seen from Table 3-3 that for the propeller-driven aircraft and for the jet aircraft the rank ordering of the single-event measures with respect to average difference does not follow the rank ordering with respect to variability. The significance of this result is unclear. However, the frequency-weighted sound levels are the most accurate single-event measures for both aircraft categories with the L_D and L_B (and L_C for the jets) showing the smallest differences between calculated and judged response. Also, it is observed from Table 3-3 that the rank

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*Accuracy as used here refers to the ability of an objective measure to predict subjective response to noise with the smallest possible absolute error.

Table 3-3 Rank Ordering of Single-Event Measures Used to Predict Subjective Response to Aircraft Noise (Propeller-Driven Aircraft and Jet Aircraft); Derived from Data Presented in Reference 25.

PROPELLER-DRIVEN AIRCRAFT				JET (TURBOJET AND TURBOFAN) AIRCRAFT			
SINGLE-EVENT MEASURE, SEM	AVERAGE DIFFERENCE (ABSOLUTE VALUES) SEM-SRS dB	SINGLE-EVENT MEASURE, SEM	STANDARD DEVIATION dB	SINGLE-EVENT MEASURE, SEM	AVERAGE DIFFERENCE (ABSOLUTE VALUES) SEM-SRS dB	SINGLE-EVENT MEASURE, SEM	STANDARD DEVIATION dB
L_D	1.0	$(L_{PN})_T$	3.0	L_B	0.3	L_D, L_{PN}	2.6
L_B	1.5	LL_Z	3.1	$(L_D)_D, L_C$	0.7	LL_S	3.1
$(L_{PN})_D$	2.4	$L_A, (L_{PN})_D$	3.2	L_P	0.9	LL_Z	3.5
$(L_D)_D$	3.7	$(L_A)_D, (L_D)_D$	3.3	L_A	2.1	$(L_{PN})_T$	3.6
$(L_{PN})_{TD}$	4.9	L_D	3.4	L_D	2.7	L_A	3.9
L_P, L_A, L_C	5.3	$LL_S, (L_{PN})_{TD}$	3.6	$(L_A)_D$	5.9	L_B	5.3
L_{PN}	6.7	L_B, L_{PN}	3.8	$(L_{PN})_D$	6.1	L_P	5.4
LL_S	7.0	L_C	4.4	LL_S	7.4	L_C	5.6
LL_Z	8.5	L_P	4.5	$(L_{PN})_{TD}$	8.1	$(L_{PN})_D, (L_{PN})_{TD}$	5.7
$(L_{PN})_T$	9.7			L_{PN}	9.3	$(L_D)_D$	5.8
$(L_A)_D$	10.1			LL_Z	11.1	$(L_A)_D$	7.3
				$(L_{PN})_T$	11.6		

LEGEND:

L_P = unweighted sound level
L_A, L_B, L_C, L_D = frequency weighted sound levels
$(L_A)_D, (L_D)_D$ = duration corrected frequency weighted sound levels
L_{PN} = perceived noise level
$(L_{PN})_T$ = perceived noise level with tone correction
$(L_{PN})_D$ = perceived noise level with duration correction
$(L_{PN})_{TD}$ = perceived noise level with tone and duration correction
LL_S = Stevens's MK VI loudness calculation procedure
LL_Z = Zwicker's loudness calculation procedure

ordering on the basis of variability is somewhat similar for both aircraft categories with the L_{PN}, LL_Z, LL_S, L_D and L_A measures showing the best correlation with subject response. With the exception of the LL_S and L_A measures, this finding is consistent with the overall results reported by Ollerhead.[25]

Considering only the propeller-driven aircraft, it may be observed from Table 3-3 that the L_{PN} measures (tone corrected and uncorrected) are improved in terms of accuracy by a duration correction, i.e., reduced average difference, while the accuracy of the frequency-weighted measures, L_A and L_D, is reduced. The variability of the L_{PN} and the frequency-weighted single-event measures appears to be little affected by a duration correction.

For the jet aircraft, the L_{PN} measures (tone corrected and uncorrected) and the L_D are improved in terms of accuracy by a duration correction while the accuracy of the L_A is reduced. However, the variability of both L_{PN} measures and the L_A and L_D measures is increased by a duration correction.

In 1971, Ollerhead[13] conducted a comprehensive paired comparisons test to assess the practical differences between a number of methods for calculating the perceived noise level of aircraft flyover sounds. A total of 119 aircraft sounds was selected for use in the investigation. The sounds were divided into four major categories: 34 jets (turbojet and turbofan), 59 propeller-driven aircraft (31 gas-turbine engined and 28 piston-engined), and 26 piston- and turbine-engined helicopeters. The sounds included outdoor recordings of flyovers, takeoffs, and landings with a wide assortment of microphone positions with respect to the flight path so that the sounds comprised a wide variation of those sounds which might be heard around mixed traffic airports. The sounds were played to a total of 32 subjects in an anechoic listening environment with individual tests performed with five or six subjects at a time. An "absolute" judged perceived equivalent level was obtained for each sound by direct or indirect comparison with a SRS consisting of an octave band of pink noise centered at a frequency of 1000 Hz. Eighteen single-event measures were ranked in terms of their ability to accurately and consistently predict the perceived levels of the sounds as compared with objective measures. Ollerhead[13] found that significant differences do exist between sets of objective measures. It was reported that in terms of consistency the complex measurement procedures including ELL_S, ELL_Z, and EL_{PN} are essentially indistinguishable.* Also statistically indistinguishable from the complex measurement procedures were the EL_D and the LL_Z.

Distinct differences were found between the applicability of the single-event measures of sounds in the four different aircraft categories. On the average, all of the single-event measures were extremely consistent for the piston-engined propeller aircraft sounds but increasingly less so for the jets, the turboprops, and the helicopters, in that order. The deficiencies of the latter groups were attributed to improper account of pure tones in the turboprop spectra and low frequency harmonic sound in the helicopter sounds. It was reasoned that tones at frequencies below 500 Hz were identified for turboprops and helicopters but could not be perceived by listeners. Ollerhead[13] concludes that only in the case of the jet sounds did the tone correction to the L_{PN} appear to perform as intended, and then the improvement was marginal. Ollerhead[13] also reported that in the case of the piston-engined propeller aircraft sounds, the correction was not required and that for turboprops the need for a correction was questionable. Ollerhead[13] suggests that the procedure used to detect and correct for tones below 500 Hz may result in overestimating the effects of these low frequency tones. However, Galloway[16] reports that Ollerhead[13] incorrectly applied the tone correction below 500 Hz and recommends reanalysis of the study data to provide better insight regarding the applicability of tone corrected EL_{PN}, especially to helicopter noise.

Additionally, Ollerhead[13] concluded that the application of a 3 dB correction per duration doubling improves the performance of the single-event measures for all aircraft categories. Finally, Ollerhead[13] reported that on the basis of accuracy and consistency the L_D is the best frequency-weighted sound level studied and, for all practical purposes, is at least as good as L_{PN} for rating aircraft noise.

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*The prefix E denotes the application of an integrated signal duration allowance.

The study results reported by Ollerhead[13] have been separated according to the following aircraft categorization: 1) GA propeller-driven (piston engine), 2) GA turboprop, 3) commercial jet (turbofan), and helicopter (piston and turbine). The GA propeller-driven and GA turboprop aircraft were defined as aircraft with gross weight not exceeding 12,500 lbs. However, two turboprop aircraft which exceeded the GA gross weight limit (19,230 lbs and 35,000 lbs) were included in the GA turboprop group since these aircraft do operate at GA airports. Only aircraft with a gross weight of 75,000 lbs or more were included in the jet aircraft category. It should be noted that of the 34 jet aircrfaft sounds included in Ollerhead's[13] investigation, 32 were commercial turbofans with gross weights exceeding 75,000 lbs.

For each aircraft category, the currently used single-event measures were rank ordered on the basis of average difference (accuracy) and variability (consistency) between the calculated and judged sound levels. The results of the rank ordering analyses are shown on Table 3-4.

With respect to accuracy, it may be seen from Table 3-4 that for each of the four aircraft categories, the L_P (unweighted sound level), EL_P, L_A, L_B, L_D, EL_D and ELL_S are among the best single-event measures of subjective response. Considering the propeller-driven piston, turboprop, and helicopter aircraft as a single aircraft category, the following have been concluded from the results presented on Table 3-4:

1. EL_P and L_A are, on the average, more accurate for the propeller-driven piston, turboprop, and helicopter aircraft than for the jet aircraft.
2. L_B and L_D are, on the average, less accurate for the propeller-driven piston, turboprop, and helicopter aircraft than for the jet aircraft.
3. L_P, EL_D and ELL_S give approximately the same degree of accuracy for all four aircraft categories.

Table 3-4 Rank Ordering of Single-Event Measures Used to Predict Subjective Response to Aircraft Noise (GA Propeller-Driven Piston, GA Turboprop, Commercial Jet, and Helicopter) Derived from Data Presented in Reference 13.

GA PROPELLER-DRIVEN (PISTON ENGINE)				GA TURBOPROP			
SINGLE-EVENT MEASURE, SEM	AVERAGE DIFFERENCE (ABSOLUTE VALUES) SEM-SRS dB	SINGLE-EVENT MEASURE, SEM	STANDARD DEVIATION dB	SINGLE-EVENT MEASURE, SEM	AVERAGE DIFFERENCE (ABSOLUTE VALUES) SEM-SRS dB	SINGLE-EVENT MEASURE, SEM	STANDARD DEVIATION dB
L_P, EL_P	0.4	LL_Z	2.1	L_A	0.0	ELL_Z	2.1
L_A	2.2	ELL_Z	2.2	L_P, EL_P	0.3	$E(L_{PN})$, ELL_S	2.4
ELL_S	2.4	EL_B, EL_D	2.4	EL_D	1.3	EL_A	3.0
L_B	2.7	ELL_S, $E(L_{PN})$	2.5	EL_B	2.9	$E(L_{PN})_T$	3.1
EL_D	3.0	L_D	2.6	ELL_S	3.0	EL_B	3.4
L_D	3.6	L_B, L_P, EL_P, EL_A	2.7	ELL_Z	4.5	LL_Z	3.6
EL_B	3.7	$E(L_{PN})_T$	2.8	L_B	5.1	L_{PN}	3.7
ELL_Z	4.3	L_A, $(L_{PN})LL_S$	3.0	$E(L_{PN})$	5.5	L_D, EL_D	3.8
EL_{PN}	4.4	$(L_{PN})_T$	3.4	L_D	6.1	LL_S	4.0
$E(L_{PN})_T$	7.1			EL_A	7.9	L_P, EL_P	4.4
EL_A	8.8			$E(L_{PN})_T$	9.5	L_A	4.5
LL_S	8.9			LL_S	10.1	L_B	4.6
LL_Z	10.5			LL_Z	11.1	$(L_{PN})_T$	4.9
L_{PN}	11.1			L_{PN}	13.3		
$(L_{PN})_T$	14.6			$(L_{PN})_T$	17.7		

Note: The prefix E denotes the application of an integrated signal duration allowance

Legend:

L_P = unweighted sound level
L_A, L_B, L_D = frequency weighted sound levels
L_{PN} = perceived noise level
$(L_{PN})_T$ = perceived noise level with tone correction
LL_S = Stevens's MK VI loudness calculation procedure
LL_Z = Zwicker's loudness calculation procedure

Table 3-4 (Cont'd) Rank Ordering of Single-Event Measures Used to Predict Subjective Response to Aircraft Noise (GA Propeller-Driven Piston, GA Turboprop, Commercial Jet, and Helicopter) Derived from Data Presented in Reference 13.

COMMERCIAL JET (TURBOFAN)				HELICOPTER (PISTON AND TURBINE)			
SINGLE-EVENT MEASURE, SEM	AVERAGE DIFFERENCE (ABSOLUTE VALUES) SEM-SRS dB	SINGLE-EVENT MEASURE, SEM	STANDARD DEVIATION dB	SINGLE-EVENT MEASURE, SEM	AVERAGE DIFFERENCE (ABSOLUTE VALUES) SEM-SRS dB	SINGLE-EVENT MEASURE, SEM	STANDARD DEVIATION dB
L_B	0.3	LL_Z	2.7	EL_P, L_D	0.3	ELL_S	3.4
EL_P	1.4	L_D	2.9	L_B	0.5	ELL_Z	3.5
L_P, L_D	1.9	EL_D, L_A, L_{PN}	3.1	ELL_S	2.4	EL_D	3.6
EL_D	2.3	$E(L_{PN})_T, LL_S, E(L_{PN})$	3.2	L_P, EL_D	3.2	$E(L_{PN}), E(L_{PN})_T$	3.7
ELL_S	2.5	ELL_S	3.3	EL_B	4.6	LL_Z, EL_B	3.9
L_A	3.1	ELL_Z	3.5	$L_A, E(L_{PN})$	4.1	EL_A, LL_S	4.3
EL_B	3.7	$(L_{PN})_T$	3.7	LL_S	4.9	EL_P	4.6
$E(L_{PN})$	4.7	EL_A	3.8	ELL_Z	5.2	L_D, L_{PN}	4.7
ELL_Z	5.0	L_B, L_P	4.2	$E(L_{PN})_T$	6.7	$L_B, (L_{PN})_T$	4.9
LL_S	6.3	E_LB	4.6	EL_A	6.8	L_P, L_A	5.0
EL_A	6.9	EL_P	5.1	L_{PN}	7.2		
$E(L_{PN})_T$	7.0			LL_Z	7.9		
LL_Z, L_{PN}	8.9			$(L_{PN})_T$	9.9		
$(L_{PN})_T$	11.6						

Note: The prefix E denotes the application of an integrated signal duration allowance

Legend:

L_P = unweighted sound level
L_A, L_B, L_D = frequency weighted sound levels
L_{PN} = perceived noise level
$(L_{PN})_T$ = perceived noise level with tone correction
LL_S = Stevens's MK VI loudness calculation procedure
LL_Z = Zwicker's loudness calculation procedure

With respect to consistency, the results shown on Table 3-4 support Ollerhead's[13] conclusion that, on the average, all of the single-event measures are extremely consistent with the least variability for the propeller-driven piston aircraft followed by the jets, turboprops, and helicopters, in that order. Also, by averaging over all aircraft categories, it may be seen that EL_D, L_D and L_A are the most consistent frequency-weighted sound level measures and that ELL_Z, ELL_S, $E(L_{PN})$ and $E(L_{PN})_T$ are the most consistent calculated sound level measures.

Considering the propeller-driven piston, turboprop, and helicopter aircraft as a single aircraft category, the following have been concluded from the results presented in Table 3-4:

1. ELL_Z is, on the average, more consistent for the propeller-driven piston, turboprop, and helicopter aircraft than for the jet aircraft.
2. L_D and L_A are, on the average, less consistent for the propeller-driven piston, turboprop and helicopter aircraft than for the jet aircraft.
3. EL_D, ELL_S, $E(L_{PN})$ and $E(L_{PN})_T$ give approximately the same degree of consistency for all four aircraft categories.

It should be noted that for all aircraft categories, including the jet aircraft, the L_{PN} with a tone correction shows extremely poor accuracy and poor consistency compared with all other single-event measures. However, applying a correction for signal duration improved both the accuracy and the consistency of the tone corrected L_{PN} for all aircraft categories.

3.1.2.2 Recent Investigations

Most of the recent psychoacoustic studies have been concerned with subjective response to helicopter and larger commercial jet aircraft noise. However, Shephard[39] recently completed an investigation of the annoyance from noise produced by a light single-engined (piston) aircraft. Using a numerical category scaling technique, 30 subjects gave annoyance ratings to a total of 25 tape recorded aircraft sounds. These sounds had peak A-weighted sound levels of between 65 and 85 dB, and 10 dB-down durations of between 2 and 45 seconds. Shepherd investigated the use of a number of single-event measures including L_A, L_B, L_C, L_D, L_{PN}, $(L_{PN})_T$, L_{EPN}, Stevens's MARK VII, and L_P. The following conclusions were reported:

- The addition of a duration correction to any of the commonly used single-event measures helps explain annoyance. The benefit of this addition depends upon the measure used and the form of the duration correction employed.
- In general, the increase in the value of the product-moment correlation coefficient obtained with the addition of a duration correction is only marginally significant for the aircraft sound investigated.
- A 5 dB- and a 20 dB-down duration correction appear to be as good as the conventional 10 dB-down duration correction.
- For the aircraft sounds investigated, the 5 dB-down duration produced consistently, though not significantly, larger product-moment correlation coefficients.

In a recent study examining the subjective response to several helicopter blade-slap characteristics, Lawton[40] reported that L_A and L_{PN} underestimated the annoyance caused by impulsive noises by approximately 2 dB. This finding was based on test results of a numerical category scaling procedure in which 40 subjects judged the annoyance (noisiness) of synthesized helicopter sounds. Using a magnitude estimation procedure, Patterson [41] et al. investigated the annoyance (noisiness) response of actual helicopter flyovers. Twenty-five subjects took part in the investigation and a DC-3 (propeller-driven) aircraft was used as a reference sound source. It was concluded that: 1) There is little difference between the L_A, L_D and L_{EPN} in predicting subjective response, 2) The equivalent continuous A-weighted sound level (L_{Aeq}) performed as well as any of the other measures, and 3) No correction for blade slap was found which improves the prediction of annoyance. Interestingly, it was reported that there were individuals whose ratings of annoyance were more consistent with the L_C and L_B frequency-weighted sound levels.

Powell[42] investigated 72 actual flyovers of two helicopters and a small single engine propeller-driven aircraft. A total of 91 subjects located indoors and outdoors judged the noisiness of the aircraft using a numerical category scaling procedure. It was concluded that:

1. No significant improvement in the noisiness predictive ability of L_{EPN} was provided by either an impulsiveness correction or an impulsiveness correction based on an A-weighted crest factor.*
2. For equal L_{EPN}, the more impulsive helicopter was consistently judged less noisy than was the less impulsive helicopter.

In two studies[43,44] conducted under FAA sponsorship concerning noise certification criteria and implementation considerations for V/STOL aircraft, a number of single-event measures were investigated to determine their validity in assessing annoyance response and to estimate noise levels that will be acceptable to communities surrounding airports. In the first study,[43] 35 subjects made both magnitude estimation and absolute acceptability judgments to both actual and simulated recordings of aircraft flyovers. A total of 32 flyover signals were presented at five different levels. The flyovers included commercial jet powered aircraft, small and medium propeller-driven piston and turboprop commuter aircraft, both single and twin engine helicopters, a V/STOL military jet fighter, a tilt wing turboprop V/STOL, and seven simulations representing STOL aircraft configurations and operations. In all, 10 different single-event measures were evaluated including L_A and L_{PN} with each corrected according to current FAR-36 procedures for tone, duration, and tone and duration combined. Stevens's MK VI and MK VII were also evaluated, but no corrections were applied to these procedures. Because the study results were not presented with respect to the individual aircraft categories, (i.e., propeller-driven piston, turboprops, helicopter, etc.), the conclusions reported in this study could not be specifically related to the GA-type aircraft.

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*The crest factor is peak sound level minus rms sound level.

However in the follow-on study[44] it was concluded that:

1. L_{PN} with the current FAR-36 duration correction procedure $(L_{PN})_D$ reliably reflects annoyance to helicopter noise.
2. No correction for "slap" or tone is required.
3. $(L_A)_D$ (duration corrected) is not significantly different from $(L_{PN})_D$ for measuring effects of helicopter noise.
4. Elimination of "heavy slap" is equivalent to a maximum of a 2 to 3dB (A-weighted sound level) reduction relative to annoyance response.

3.1.3 Subjective Response Measures to Multiple-Events

3.1.3.1 Types of Multiple-Event Measures

Prediction and understanding of community response to noise cannot be made solely on the basis of the physical parameters and acoustical characteristics of the noise exposure. For this reason, laboratory studies of human response to aircraft noise do not provide sufficient information alone to allow an adequate understanding of community reactions or to establish limits of acceptable noise exposure. As a result, opinion (social) surveys have been used to collect data concerning the degree of dissatisfaction or annoyance experienced by individuals exposed to various levels of aircraft noise. These data are then correlated with objective measures that account for the aircraft's noise characteristics and the volume of aircraft activity occurring over a specified period of time. These objective measures, or multiple-event measures, are then used to scale community or group response (as opposed to the response of any one individual) to various cumulative magnitudes of aircraft noise exposure.

The first studies concerned with community reaction to aircraft noise were undertaken in the United States during the early 1950s.[45] In the late 1950s, surveys were conducted around several United States Air Force military air bases to identify noise problems associated with the advent of jet aircraft.[46] In 1961 and 1967, comprehensive surveys were performed around London (Heathrow) Airport.[47,48] From 1967 to 1971, three separate survey efforts were conducted in the United States to investigate community reaction to commercial jet aircraft noise around seven major airports (Boston, Chicago, Dallas, Los Angeles, Miami, and New York) and two smaller city airports (Chattanooga and Reno/Sparks).[49,50]

The first multiple-event measure proposed for aircraft noise was the Composite Noise Rating (CNR), developed specifically for use in airport/land use planning. For takeoff and landing operations, CNR is defined mathematically by:[49,50]

$$\mathrm{CNR} = 10 \log_{10} \sum_{j} \mathrm{antilog}\left\{[(L_{PN})_j + 10 \log_{10} (N_{Dj} + 20\, N_{Nj})]/10\right\} - 12 \qquad (3\text{-}1)$$

where j is a single class of operation (aircraft type, type of operation, flight path, etc.) producing a particular type of noise event at the point in question, N_{Dj} and N_{Nj} are the number of daytime and nighttime occurrences in that class, respectively, and $(L_{PN})_j$ is the maximum perceived noise level in that class.

Two points should be noted regarding the CNR formulation:

1. It deals specifically with aircraft noise "events" and excludes other types of noise.
2. The night penalty, which is equivalent to 13 dB, is based on an assumed increased community sensitivity during the night hours.

The CNR predictive equation is of particular importance because it formed the basis for many later multiple-event measures.

As a result of a number of criticisms of the CNR measure and for a number of other reasons, the Noise Exposure Forecast (NEF) procedure was developed under the sponsorship of the FAA in 1967.[51] The NEF is defined mathematically by:[52]

$$\mathrm{NEF} = 10 \log_{10} \sum_{j} \mathrm{antilog}\left\{[(L_{EPN})_j + 10 \log_{10}(N_{Dj} + 16.67\, N_{Nj})]/10\right\} - 88 \qquad (3\text{-}2)$$

where $(L_{EPN})_j$ is the "effective" perceived noise level.

The NEF differed from the CNR in three respects:

1. The perceived noise level concept was replaced by the effective perceived noise level measure which accounted explicitly for the effects of flyover duration and discrete frequency components.
2. The generalization of equivalent noise level which was obtained through continuous integration or summation and which could include the effects of ambient noise.[53]
3. The difference in the constants used as normalization factors to adjust the measures for different volumes of operation.

The third measure, the Noise and Number Index (NNI) was developed in England as an outgrowth of the social surveys conducted around Heathrow Airport. On the basis of the first survey, the NNI was developed from a best fit average response, assuming a priori dependence on both noise level and number of events. The NNI is given by:[54]

$$\text{NNI} = 10 \log_{10} \frac{1}{N_j} \left\{ \sum_j \text{antilog} \; [(L_{PN})_j/10) + 15 \log \; N_j] - \right\} 80 \qquad (3\text{-}3)$$

where N_j is the total number of operations or events in a specified period of time.

Investigations conducted in several other countries used the results of attitudinal surveys and physical noise measurements to develop a number of additional relationships between community response and a measure of noise exposure. As a result of these extensive efforts to quantify community response to aircraft, as well as other noise sources, a number of nationally and internationally recognized multiple-event measures have been developed. Some of these measures include the German Mean Annoyance Level (Q), the French Isopsophic Index (*N*), the South African Noise Index (NI), the International Civil Aviation Organization's Weighted Equivalent Continuous Perceived Noise Level (WECPNL), the Netherlands Total Noise Load (B), the United States' Day-Night Sound Level (L_{dn}), the

United Kingdom's Noise Pollution Level (NPL) and Traffic Noise Index (TNI). Another multiple-event mesasure used by the State of California for purposes of land use planning around airports is the Community Noise Equivalent Level (CNEL). However, for most purposes, CNEL is equivalent to the L_{dn}.

Mathematical expressions for these multiple-event measures are presented in Reference 54. However, most of these measures bear a strong resemblance to the CNR, NEF, and NNI measures with only minor differences in computational detail. For example, the L_{dn} is given by:[16]

$$L_{dn} = 10 \log_{10} \sum_{j} \text{antilog} \left\{ [(L_S)_j + 10 \log_{10} (N_{Dj} + 10 N_{Nj})]/10 \right\} - 49.4 \quad (3\text{-}4)$$

where $(L_S)_j$ is defined as the Sound Exposure Level[52] for the j-th noise level or event.

3.1.3.2 Factors Affecting Multiple-Event Measures

In the development of many of the multiple-event measures, it has been generally assumed that community response is related to a measure of the acoustical energy, either total or average, experienced over a specified interval of time. Based on this underlying assumption, equivalent-energy models have been formulated, according to which a 10-fold change in either acoustical energy or number of events is equivalent to a 10 dB change in noise exposure level. Additionally, most of the multiple-event measures include a weighting factor to account for varying noise sensitivity of people with time of day. In some cases, adjustments for seasonal variations may be incorporated. In the following sections, the effects of the number of events and the time-of-day weighting adjustments on the validity and accuracy of multiple-event measures will be discussed. Emphasis is focused on these two "acoustical factors" since they are generally considered to be two of the most important parameters affecting the correlation between noise exposure and community response.

A. Effect of Number of Events

Based on an equivalent-energy model, N identical noise events will sum in accordance with the relationship, $K \log_{10} N$ where $K = 10$.

With only a few exceptions,* this summing relationship is incorporated in most of the existing multiple-event measures used to quantify aircraft noise exposure.

Based on the 1961 London (Heathrow) Airport noise and operations data used to develop the NNI, Galloway and Bishop[53] have compared the mean annoyance scores determined from the social survey data with calculated CNR values. The relationship between CNR and average annoyance is shown in Figure 3-2. It may be seen that the CNR rating fits the subjective judgments of noise exposure quite well, in spite of the different manner in which the number of events are accounted for in the CNR and NNI equations.

Galloway[16] reports that based on analyses of the second social survey around Heathrow Airport (1967), the degree of correlation between community response and noise exposure is, in general, quite insensitive to the value of K used in the summing relationship over the range of from 2 to 22, but that some form of $K \log_{10} N$ is useful in assessing annoyance response. In a recent investigation of the trade-off effects of aircraft noise level and number of events, Rice[55] presents study results which tend to support the use of $K = 10$ as an appropriate value in the summing relationship. However, Rice notes that based on the results of the investigation it appears that the total number of events influences annoyance judgments with optimum values of K being somewhat proportional to the number of events. In 1972, Tracor[50] reported the results of a study to investigate the effect of commercial jet aircraft noise from smaller city (commercial aviation) airports and to compare these data with those from an earlier study[49] of the effects of commercial jet aircraft noise exposure in big cities. The results indicated that a significant difference exists between the smaller cities and the bigger cities with respect to the relationship between annoyance and aircraft noise exposure at CNR values below 125. It was reported that the number of highly annoyed persons in the smaller cities was less than half that in the larger cities at these CNR values. It was concluded that one of the factors most likely responsible for the difference in annoyance response was the relatively lower aircraft traffic volume observed at the smaller city airports.

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*Some of these exceptions include the Mean Annoyance Level ($\bar{Q}$), the Noise and Number Index (NNI), and the Total Noise Load (B).

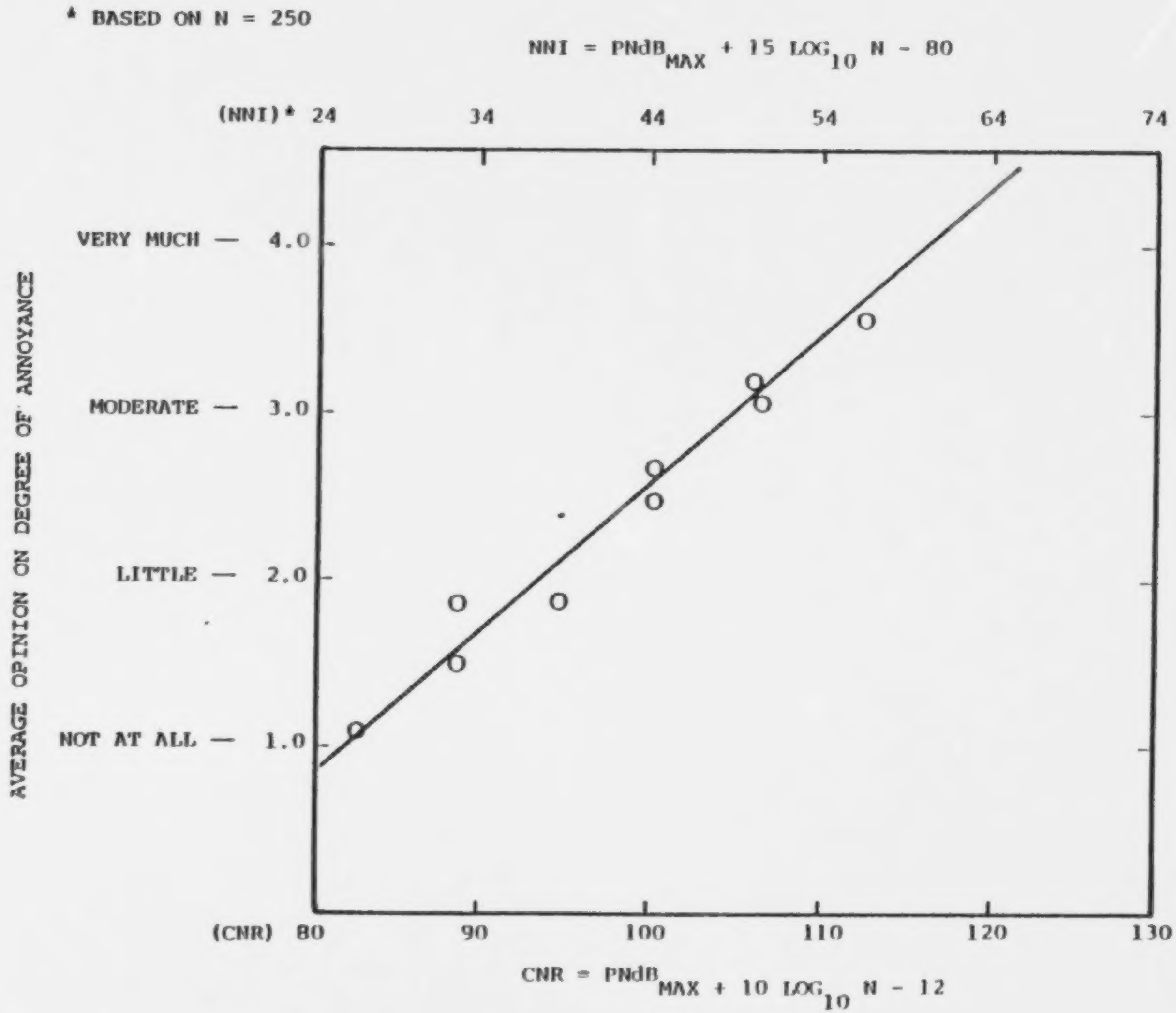

Figure 3-2. LONDON (HEATHROW) AIRPORT SOCIAL SURVEY ANNOYANCE RESPONSE AS A FUNCTION OF CNR AND NNI; DATA FROM 1961 SURVEY (from Galloway and Bishop, Reference 53).

Rylander et al.[56,57,58] reports that, based on data from a number of aircraft noise social surveys, the degree of annoyance expressed by a noise exposed population is closely related to the peak noise level of single flyovers. For areas exposed to a low number of daily operations (35 or less) the extent of "very annoyed" in the population is essentially zero provided the noise levels (of single events) do not exceed a maximum A-weighted sound level of 90 dB, at which point the percent highly annoyed increases markedly. For areas exposed to a high number of operations (50 or more) an increase in the extent of "very annoyed" is found when the noise level of the noisiest aircraft exceeds 70 to 75 dB. In these high exposure areas it is reported that the increase of mean annoyance with maximum or peak A-weighted noise levels up to 95 dB is linear with a correlation coefficient of 0.99.

Connor and Patterson[59] have recently investigated the general validity of the "equivalent-energy" and the "peak A-weighted sound level" concepts as applied to community annoyance to aircraft noise. Using data previously gathered around nine U. S. airports,[49,50] it was concluded that annoyance response follows neither concept. Additionally, it was reported that:

1. Annoyance response can be better predicted by treating level and number of events as separate variables, rather than combining them in a single-number exposure parameter.
2. Annoyance increases steadily with energy-mean level for constant daily operations.
3. Annoyance increases with numbers of operations up to 100-199 per day, then decreases for high numbers.
4. The statistical distribution of individual annoyance varies with level and number of events, thus influencing the behavior of any single noise measure, such as a mean or a percentile value, relative to that of another measure.

B. Period of the Day

Most of the multiple-event measures divide the day into two or more discrete time periods. Some of these periods may be weighted to account for variations in community sensitivity to noise during these periods. These multiple-event measures usually divide the day into two periods, daytime and nighttime, or three periods, daytime, evening and nighttime.* Regardless of whether the day is divided into two or three time periods, nighttime noise exposure or noise levels are generally weighted by an addtional 10 dB. The 10 dB penalty treats nighttime sounds as though they were either 10 dB more intense than they actually are. However, specific documentation in support of the 10 dB nighttime penalty is scant. It appears that the selection of a 10 dB value was made more on the basis of judgment than on actual scientific findings. Furthermore, justification for the use of a 10 dB nighttime penalty has been based primarily on the basis that there is no strong evidence to contradict its use. For example, the use of a 10 dB penalty applied to nighttime exposure in the NEF procedure appears to have been carried over from the earlier CNR scheme. However, little quantitative data to support a 10 dB nighttime weighting have ever been presented for either the CNR or the NEF procedures.

The EPA "Levels Document"[52] based the choice of 10 dB for the nighttime weighting of noise levels on its extensive prior usage and on data obtained from 55 community noise surveys showing the time variations of of environmental noise level over a 24-hour period. Support for the 10 dB nighttime penalty was based on the following three assumptions: 1) the same noise environment is considered more disturbing during nighttime than daytime, 2) the exterior background noise levels tend to drop by 10 dB or more during the night in most communities, and 3) the reduced activity inside homes during the nighttime contributes to the general lowering of interior noise levels. Thus, it was concluded that noise events occurring during the nighttime should be weighted to reflect the increased intrusiveness of their disturbance. Furthermore, the "Levels Document" stated that the 10 dB nighttime penalty was appropriate because it would: 1) assure that the day sound level (L_d) and the nighttime sound level(L_n) contributed about equally to L_{dn} in low noise environments (45 to 55 dB), and 2) apply pressure towards a 24-hour reduction in noise levels in high noise environments (65 to 90 dB).

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*For a two period day the daytime is from 7 a.m. to 10 p.m. and the nighttime is from 10 p.m. to 7 a.m. For a three period day the daytime is from 7 a.m. to 7 p.m., evening is from 7 p.m. to 10 p.m., and nighttime is from 10 p.m. to 7 a.m.

Recent studies have presented data which suggest that a 10 dB penalty for nighttime periods may not be the appropriate weighting value (e.g., Borsky,[60] Fidell and Jones,[61] Ollerhead,[62,63] and Man-Acoustics and Noise[64]). Based on results from a study of variations in community annoyance around New York (JFK), Borsky[60] suggests that the 10 dB penalty is much too high. Fidell and Jones [61] investigated the effects of reducing nighttime noise exposure in a community near Los Angeles International Airport by 25 to 30 dB (A-weighted) between 11:00 p.m. and 6:00 a.m. Based on the results of this investigation, it was reported that the reduction in noise exposure had no appreciable short-term effect on the reported sleeping habits, communications interference, or beliefs in danger or misfeasance of the affected population, nor did it significantly change their levels of annoyance, whether annoyance was specific to speech and sleep interference or general to aircraft noise. It was suggested that a possible explanation may lie in the nighttime penalty, indicating a possibility that 10 dB is too large. In a recent study by Ollerhead[62] concerning the relative annoyance of aircraft noise in communities around London (Heathrow) Airport, it was reported that aircraft noise is considered to be worse, in terms of disturbance and annoyance, during the evening than during the day (one evening aircraft flyover being equivalent to four daytime aircraft flyovers) and that aircraft noise causes little or no disturbance to most people at night, presumably because they sleep through it. However, people who are distrubed at night consider the disturbance to be more severe and more annoying than during the waking day and evening hours. It was concluded that with respect to the structure of multiple-event measures used to predict community annoyance from aircraft operations, an evening weighting of about 5 or 6 dB seems more appropriate and that the commonly used weighting of 10 dB is probably too large and extends over too long a period of time. It was suggested that perhaps the evening time period be extended to 1:00 a.m. to cover the critical "falling asleep" phase and to apply a zero weighting for the remainder of the night.

In a recent investigation to determine airport noise levels that are compatible with residential living activities, Man-Acoustics and Noise[64] reported results which strongly support Ollerhead's[62] conclusions regarding the penalties for nighttime flyover intrusions. In this study, community noise simulation systems were placed in the homes of twenty-four families that were not previously impacted by actual airport noise. Four different airport noise conditions were simulated. Three conditions involved day flights of 150 commercial aircraft (2,3,and 4-engine turbojet and turbofan) producing average NEF values of 36.9, 32.5, and 26.9. The fourth condition added 18 night flights (10 p.m. to 7 a.m.) which resulted in a mean NEF of 32.9. Based on the findings of this study, it was concluded that:

1. Interference and general annoyance was highest in the evening time (7 p.m. to 10 p.m.);
2. The 10 dB penalty for night flights is too large and could be reduced to 5 or 6 dB, a weighting value which would more accurately reflect community response to airport noise environments.

An additional relevant finding was that, on the average, participants tended to underestimate the number of flyover intrusions they were actually experiencing, suggesting the possibility that they were responding primarily to the louder flyovers.

3.1.3.3 Comparison of Multiple-Event Measures Used to Assess Community Response to Aircraft Noise Exposure

A. Theoretical Comparisons

A number of studies have compared some of the currently used multiple-event measures by computing single-number ratings for each measure using identical noise and operational parameters. The rating values for each multiple-event measure are then compared (generally on the basis of the number of operations) to determine the degree of correlation.

Galloway and Von Gierke[65], for example, compared the CNR, NNI and $\bar{Q}$ on the basis of the number of daytime operations for a situation where the average maximum perceived noise level was 110 dB with a duration of 15 seconds. It was concluded that the differences among these three procedures are very small compared to the overall uncertainty in measuring community reaction. However, both NNI and $\bar{Q}$ provide a higher penalty on number of operations above 50 per day for a given noise level than does CNR.

Serendipity[66] compared the CNR, NEF and NNI on the basis of the number of daytime operations for two different cases: 1) with equal base noise measures (i.e., $L_{PN} = (L_{PN})_{max} = L_{EPN}$), and 2) with unequal base noise measures. For the first case the following relationships were determined:

$$NEF = CNR - 76$$
$$CNR = NNI + 68 - 5 \log_{10}N$$
$$NEF = NNI - 8 - 5 \log_{10}N$$

where N is the total number of operations. For the second case, the relationships were given by:

$$NEF = CNR + (L_{EPN} - L_{PN}) - 76$$
$$CNR = NNI + [L_{PN} - (L_{PN})_{max}] + 68 - 5 \log_{10}N$$
$$NEF = NNI + [L_{EPN} - (L_{PN})_{max}] - 8 - 5 \log_{10}N$$

Galloway[16] has compared a number of prominent multiple-event measures on the basis of the number of daytime operations assuming an effective duration of 10 seconds, a maximum L_{PN} and L_{EPN} of 110 dB, and the assumption that L_A is approximately 13 dB less than L_{PN}. The measures compared included L_{dn}, CNEL, WECPNL, B, $\bar{Q}$, N, NNI, NEF, and CNR. This comparison is shown in Figure 3-3. On the basis of this comparison, Galloway[16] concludes that all of the measures are highly correlated, and that most are conceptually identical for all practical purposes, differing only in minor detail and, thus, social surveys can be correlated on the basis of any of the rating measures.

It should be noted that in all of the above comparison studies, the expressions used as a basis for comparison were general, or only approximations, to the actual multiple-event equations, applicable to a limited set of noise and operational conditions (i.e., a fixed noise level and effective time duration, and only daytime operations considered). Additionally, the assumed relationships among the single-event measures used to compute the multiple-event measures are only approximations based on averages of measurement data. For example, the differences between L_{EPN} and L_{PN} or L_{PN} and L_A, and the effective time duration of an aircraft flyover vary as a function of distance from the aircraft. Under

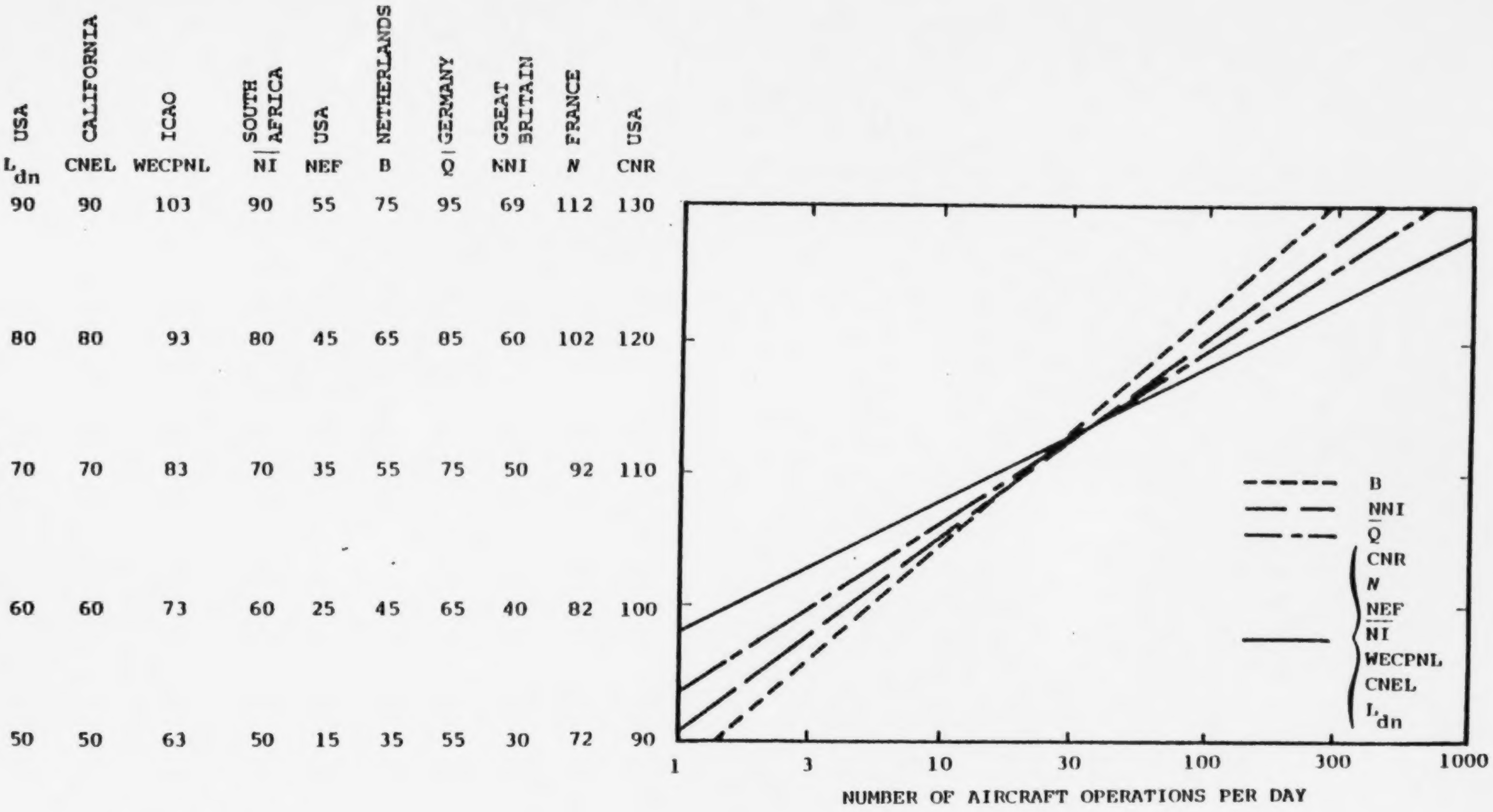

Figure 3-3. COMPARISON OF MULTI-EVENT MEASURES OF AIRCRAFT NOISE EXPOSURE (from Galloway, Reference 16).

more realistic conditions, the relationships among the multiple-event measures would be, most likely, somewhat different than those reported. However, because all of the measures will increase or decrease proportionally with sound pressure level and number of operations, a high correlation would still be expected.

The EPA "Levels Document"[52] states that there is no fixed relationship between L_{dn} and CNEL, CNR, or NEF due to differences between the L_A and the L_{PN} frequency weightings and the allowance for duration, as well as the minor differences in approach to adjusting for nighttime noise events. However, the following approximate relationships were given:

$$L_{dn} \doteq \text{CNEL}$$

$$L_{dn} \doteq \text{NEF} + 35$$

$$\text{NEF} \doteq \text{CNR}-70$$

B. Empirical Comparisons

A number of studies have compared some of the currently used multiple-event measures by computing single-number ratings for each measure using the same field measurement data. These rating values are compared to determine the relationships among the multiple-event measures and to determine their degree of correlation.

Using acoustical measurement data obtained around seven U.S. airports, Tracor[49] reports that the CNR, NNI* and NEF are practically interchangeable and highly intercorrelated, particularly in the range expected to be annoying. The following relationships and corresponding correlation coefficients were reported:

$$\text{CNR} = \text{NEF} + 72 \quad (r = 0.90)$$

$$\text{CNR} = \text{NNI} + 56 \quad (r = 0.99)$$

The correlation coefficient between NEF and NNI was given as $r = 0.88$, however no relationship was given.

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*NNI was defined mathematically in this study by the following expression:

$$\text{NNI} = 10 \log_{10} \left[\text{antilog} \left(\frac{\text{NNI}_d}{10} \right) + \text{antilog} \left(\frac{\text{NNI}_n + 17}{10} \right) \right]$$

where NNI_d and NNI_n are the values determined for day and night, respectively.

Using the results of a number of social surveys concerning aircraft noise, Schultz[67] presents relationships between L_{dn} and NNI. These relationships are shown in the following table:

Survey	L_{dn} = a NNI + b a	b
London Heathrow (1961)	0.760	37.5
Swedish (1972)	0.877	31.7
Swiss (1973)	0.833	33.3
London Heathrow (1967)	0.855	33.5

A general relationship between L_{dn} and NNI has been determined by averaging the Heathrow (1961), Swedish, and Swiss equations and is given as $L_{dn} = 0.82\ \text{NNI} + 34.2$.

C. Relationship Between Multiple- and Single-Event Measures

It is generally agreed that the annoyance response of a community exposed to aircraft noise is adequately predicted by an acoustical energy summation model. However, alternative models such as the "peak A-weighted sound level" concept have been recently proposed but have thus far not received broad support. It would be of some interest to examine the relationship between the maximum or peak levels observed for a number of independent time-varying events, such as aircraft flyovers, and resulting cumulative noise exposure levels measured at the same locations. The L_{dn} multiple-event measure was selected for this evaluation.

For a series of single-event noises, L_{dn} can be estimated by the following expression:[52]

$$L_{dn} = L_{Amax} + 10 \log_{10} (D/2) + 10 \log_{10} (N_d + 10N_n) - 49.4 \qquad (3\text{-}5)$$

where L_{Amax} = maximum or peak A-weighted sound level, dB

D = duration of the noise signal measured from the 10 dB-down points, seconds

N_d = total number of daytime events

N_n = total number of nighttime events.

For simplicity, it will be assumed that all of the single-event noise signatures are identical and therefore, all will have equal L_{Amax} and D values. Schultz[67] has presented a relationship between the 10 dB-down duration and the L_{Amax} occurring during an aircraft flyover. This relationship is given as:

$$D = -0.634\, L_{Amax} + 73.2, \text{ seconds} \qquad (3\text{-}6)$$

Substituting this expression into equation 3-5 and letting X represent the percentage of nighttime flights (i.e., $X = 100 \dfrac{N_n}{N_d + N_n}$) the L_{dn} equation becomes:

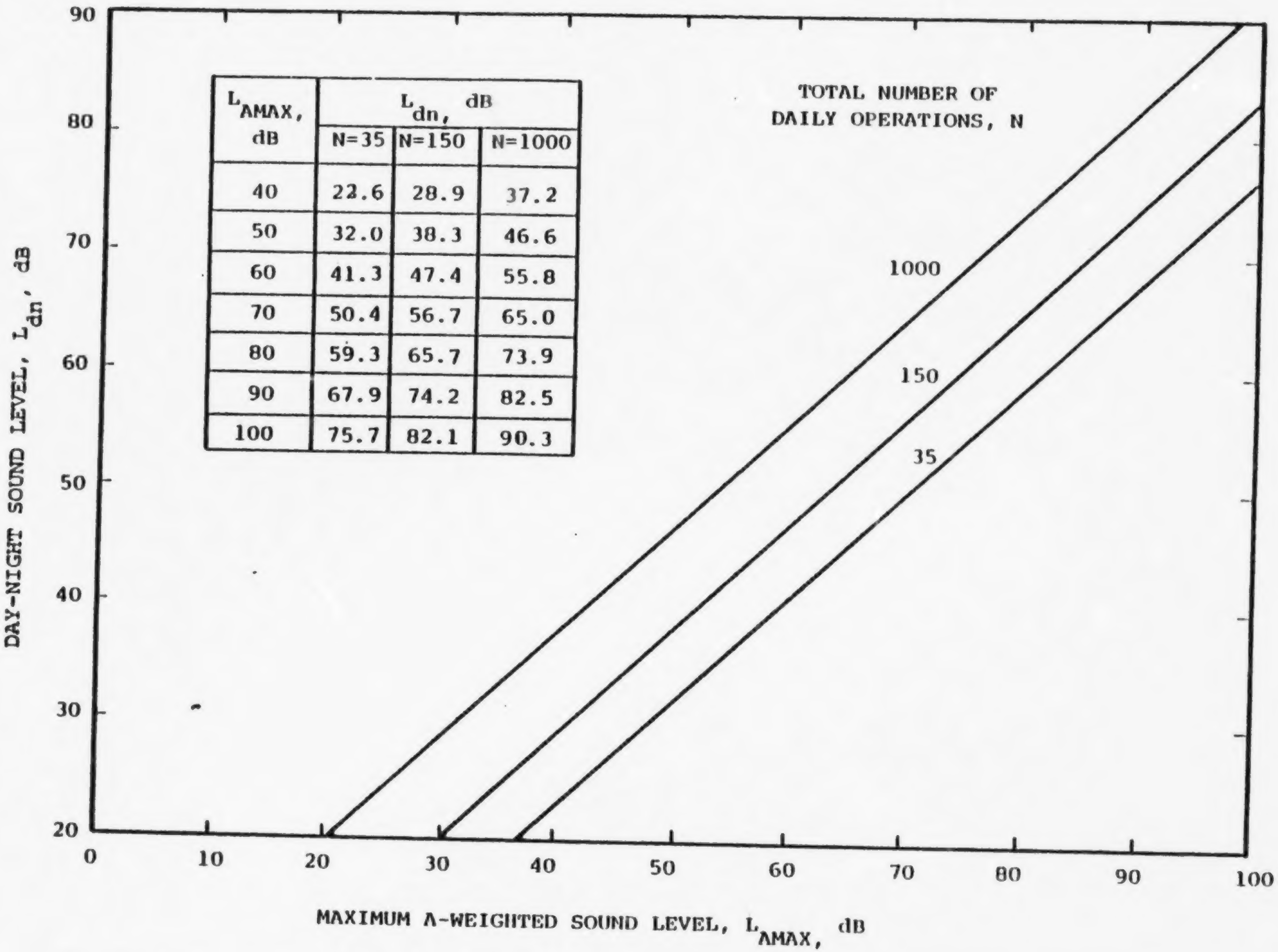
$$L_{dn} = L_{Amax} + 10 \log_{10} N + 10 \log_{10} (1 + 0.09X) + 10 \log_{10} (-0.317\, L_{Amax} + 36.6) - 49.4 \qquad (3\text{-}7)$$

where N is the total number of daily flights, i.e., $N = N_d + N_n$.

Using equation 3-7, relationships between L_{dn} and L_{Amax} for various combinations of total daily operations and percentage of nighttime operations can be examined.

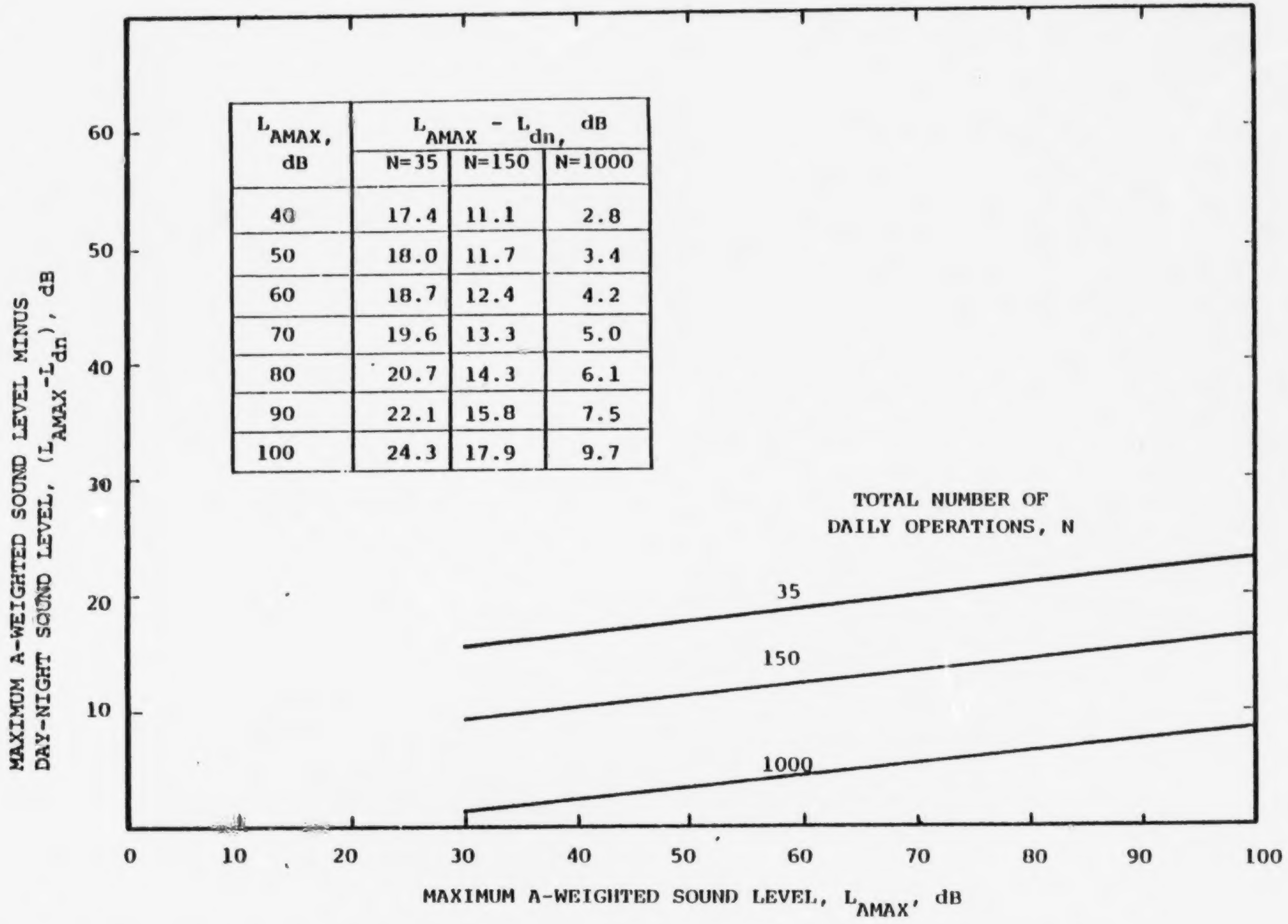
Assuming 10 percent nighttime operations, Figure 3-4 shows L_{dn} as a function of L_{Amax} and total number of daily operations. Figure 3-5 shows the difference between L_{Amax} and L_{dn} as a function of L_{Amax} and total number of daily operations. Three daily traffic volumes have been shown in each figure: 35, 150, and 1000 operations per day.

Figures 3-4 and 3-5 show the trading relationship between noise level and total number of events, characteristic of the equivalent-energy models. They also provide insight regarding the validity of the "peak A-weighted sound level" stimulus/response model proposed by Rylander[56,57,58] et al. According to these authors, for areas exposed to daily operations



L_{AMAX}, dB	L_{dn}, dB		
	N=35	N=150	N=1000
40	22.6	28.9	37.2
50	32.0	38.3	46.6
60	41.3	47.4	55.8
70	50.4	56.7	65.0
80	59.3	65.7	73.9
90	67.9	74.2	82.5
100	75.7	82.1	90.3

Figure 3-4. DAY-NIGHT SOUND LEVEL AS A FUNCTION OF MAXIMUM A-WEIGHTED SOUND LEVEL AND TOTAL NUMBER OF DAILY OPERATIONS; 10% NIGHTTIME OPERATIONS.



L_{AMAX}, dB	L_{AMAX} - L_{dn}, dB		
	N=35	N=150	N=1000
40	17.4	11.1	2.8
50	18.0	11.7	3.4
60	18.7	12.4	4.2
70	19.6	13.3	5.0
80	20.7	14.3	6.1
90	22.1	15.8	7.5
100	24.3	17.9	9.7

Figure 3-5. L_{Amax} MINUS L_{dn} AS A FUNCTION OF MAXIMUM A-WEIGHTED SOUND LEVEL AND TOTAL NUMBER OF DAILY OPERATIONS; 10% NIGHTTIME OPERATIONS

of 35 or less, the percent "very annoyed" in the population is essentially zero provided the noise levels (of single events) do not exceed a maximum of 90 dB, at which point the percent highly annoyed increases markedly. Also, for areas exposed to daily operations of 50 or more, an increase in the percent "very annoyed" is found when the noise level of the noisiest aircraft exceeds 70 to 75 dB. From Figure 3-4 it may be seen that for 35 total daily operations (assuming 10 percent nighttime operations) a change in maximum noise level of from 40 to 90 dB, results in a corresponding change in L_{dn} of from 23 to 68 dB. Assuming ambient L_{dn} noise levels of 60 dB or less, the aircraft operations do not begin to contribute significantly (on an energy basis) to the noise environment (or are not noticed) until their maximum A-weighted noise level approaches 80 to 90 dB. However, for total daily operations of 150 or more, the contribution of the aircraft noise to the total L_{dn} becomes comparable to that of the assumed ambient at maximum A-weighted noise levels of from 70 to 75 dB. For this noise level range (70 to 75 dB), it may be seen from Figure 3-4 that the L_{dn} contributions from a 1000 daily aircraft operations would exceed an ambient level of 60 dB by from 5 to 10 dB. Additionally, increases in the maximum A-weighted levels would result in proportional increases in the total L_{dn}. These increases could occur even for the situation where the noisiest aircraft represented only a small percentage of the total number of daily operations. For example, if the traffic volume at an airport is 185 operations per day with 35 (19 percent) operations performed by the noisiest aircraft, it may be seen from Figure 3-4 that if the quieter and noisier aircraft produce maximum A-weighted levels of 70 dB and 90 dB, respectively, the noisier aircraft would control the total L_{dn}. This is, of course, an extreme case but it serves to illustrate the point.

It is also interesting to note that, as shown on Figure 3-5, as the total number of daily operations increases, the difference between L_{Amax} and L_{dn} decreases. The implication being that under certain operational conditions, the maximum A-weighted noise level could serve as an adequate noise exposure and response measure.

3.1.4 Community Response to Aircraft Noise

There is little doubt that environmental noise interferes with and disrupts an extensive range of human activities. The subjective impressions of the noise, and the activity interference and disruption it produces, are believed to contribute significantly to the general feeling of annoyance. However, it is generally agreed that these two contributors alone cannot adequately predict the degree of induced annoyance experienced by individuals living in the vicinity of noise sources. In fact, the results of many studies have shown poor correlation between individual response and measured physical characteristics of the noise environment. Typical results from community noise surveys show that less than one quarter of the variance in individual annoyance reactions can be attributed to physical noise exposure. The remaining variance is believed to be caused by differences in sensitivity to annoyance by noise (or noise annoyance susceptibility) among individuals at the same exposure level. Earlier annoyance prediction models accounted for these differences statistically in two ways: 1) by averaging the responses of individuals and using the median response as a prediction measure, and 2) by incorporating measures of psycho-social variables* (or intervening nonacoustical variables) which are purported to affect annoyance independently of noise exposure. Although both methods increase the correlation between annoyance response and noise exposure level, there is some question regarding the reliability of these methods, particularly with regard to establishing criterion levels to assess community noise impact.

McKennell[68] has pointed out a number of possible limitations of the use of an average or "central tendency" response relationship. First, the average response does not provide information regarding the nature and extent of the variation in annoyance reponse. Second, the average response relationships are constructed from particular combinations of psycho-social factors that existed at a particular point in time in a particular locality.

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*Some of these variables include: 1) opinions about the effects of aircraft noise on health, fear of aircraft crashes, attitudes about the preventability of the noise exposure (misfeasance), and attitudes regarding the importance

Generalizing these results to other localities or to the future in the same locality implicitly assumes that the attitude structure in these other situations would replicate that found in the particular survey. It is evident that this particular asssumption would be invalid if there were changes in the mix of relevant psycho-social attitudes in the population or if the mix is different among the populations being compared. Finally, surveys designed to establish the central tendency run the risk of regional biases which could distort, weaken, or even reverse the expected central tendency result.

Schultz[67] suggests that the importance of the nonacoustical variables have been overemphasized and that a possible reason for the low correlation between individual annoyance response and noise exposure level has been the poor handling of the acoustical variables. Schultz[67] also suggests that, with respect to earlier noise surveys, half of the sample population at each noise expsoure level who respond below the central tendency have simply not heard the noise measured in the survey. The principal reason for this is attenuation of the noise relative to the measurement location due to distance, house orientation, shielding by other buildings or terrain, and noise reduction through the building structure itself.

Schultz[67] proposes that compared with the central tendency concept, a more meaningful and useful method for predicting community response to noise exposure would be one based on "percent highly annoyed". In addition to the high correlation between the noise exposure and the expressed subjective reaction, the use of percent highly annoyed is supported on the basis of the following:

1. The median response is much more difficult to translate from one annoyance scale to another, in everyday terms that are understood by politicians and policy makers;
2. "Percent highly annoyed" carries a common-sense import that average response completely lacks;
3. Average annoyance response is distorted by the responses of the "supersensitives" and the "imperturbables";
4. The median response does not adequately describe that part of the population whose expressed annoyance actually changes with differences in noise exposure;
5. The median response to noise corresponds essentially to "no complaints" and is not dealing with the community noise problem at all.

Based on data obtained from a number of aircraft noise social surveys, the EPA "Levels Document"[52] presents two linear relationships between percentage of the exposed population highly annoyed and noise exposure* specified in terms of outdoor day-night sound level. These relationships were developed from the first London Heathrow Airport survey, and from the combined results of the second London Heathrow Airport survey and eight U.S. air carrier airport surveys. The combined survey relationship was developed from data representing "moderate" responses to the attitudes of "fear" and "misfeasance". Both relationships, along with the combined results of the two London-Heathrow surveys and the eight U.S. air carrier airport surveys, are shown in Figure 3-6.

Based on the results of eleven social surveys concerning the noise from aircraft, street traffic, expressway traffic, and railroads, Schultz[67] has recently developed a generalized relationship between percent highly annoyed and outdoor noise level in terms of L_{dn}. The eleven surveys considered in the evaluation include the following:

1. First Heathrow Aircraft (1961)
2. French Aircraft (1966)
3. Second Heathrow Aircraft (1967)
4. Munich Aircraft (1969)
5. Paris Street Traffic (1969)
6. Swiss Road Traffic (1972)
7. London Street Traffic (1972)
8. Swedish Aircraft (1972)
9. Swiss Aircraft (1973)
10. French Railroad (1973)
11. Urban Noise Survey-EPA (1974)

The data used to develop the generalized relationship is shown in Figure 3-7. Aircraft data points are represented by solid circles while the non-aircraft data points are represented by solid squares. Using statistical regression techniques, best fit equations have been developed using the following three sets of data:

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*Figures D-10 and D-13 in Appendix D of Reference 52.

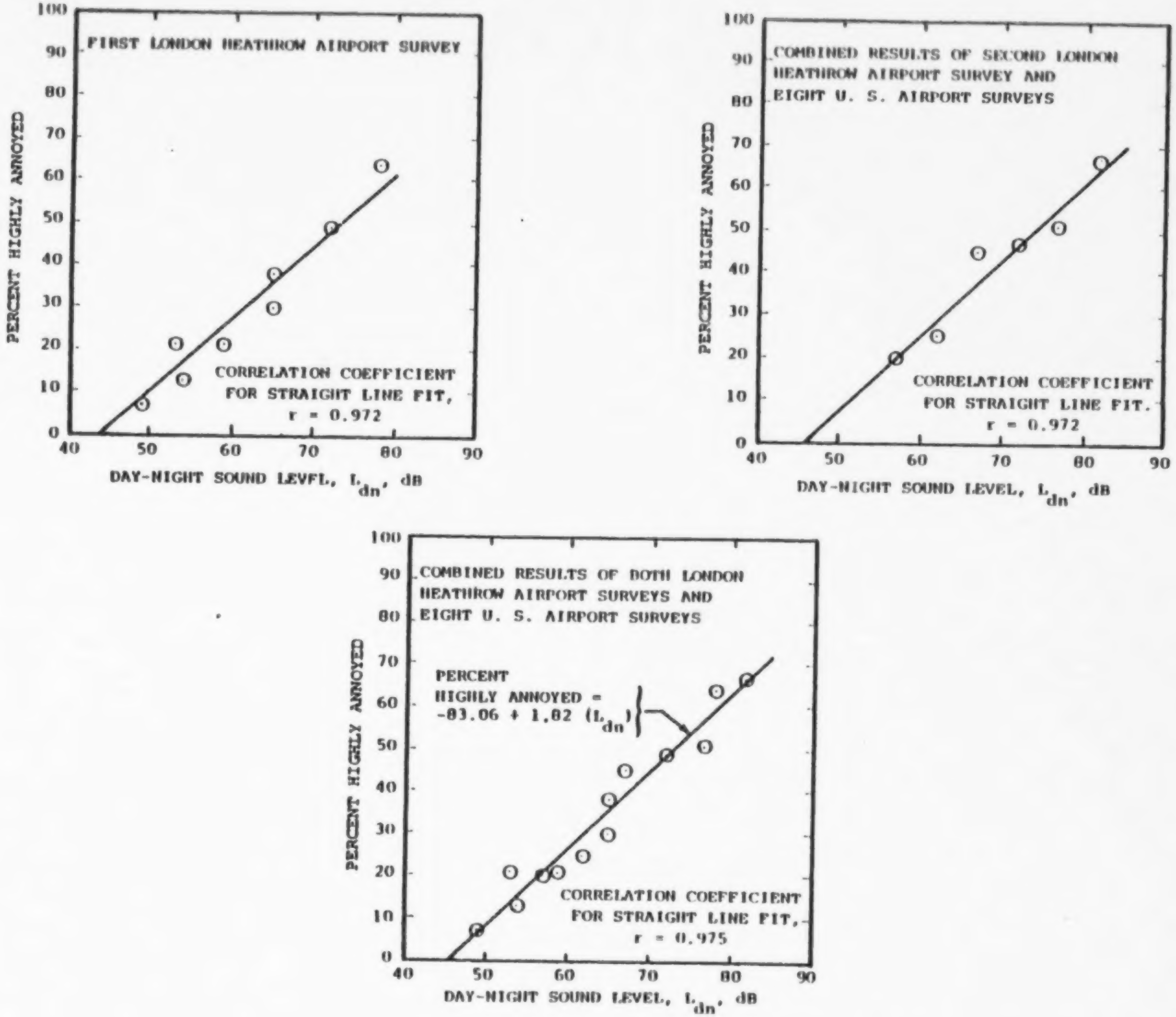

Figure 3-6. PERCENT HIGHLY ANNOYED AS A FUNCTION OF DAY-NIGHT SOUND LEVEL (from EPA "Levels Document," Reference 52).

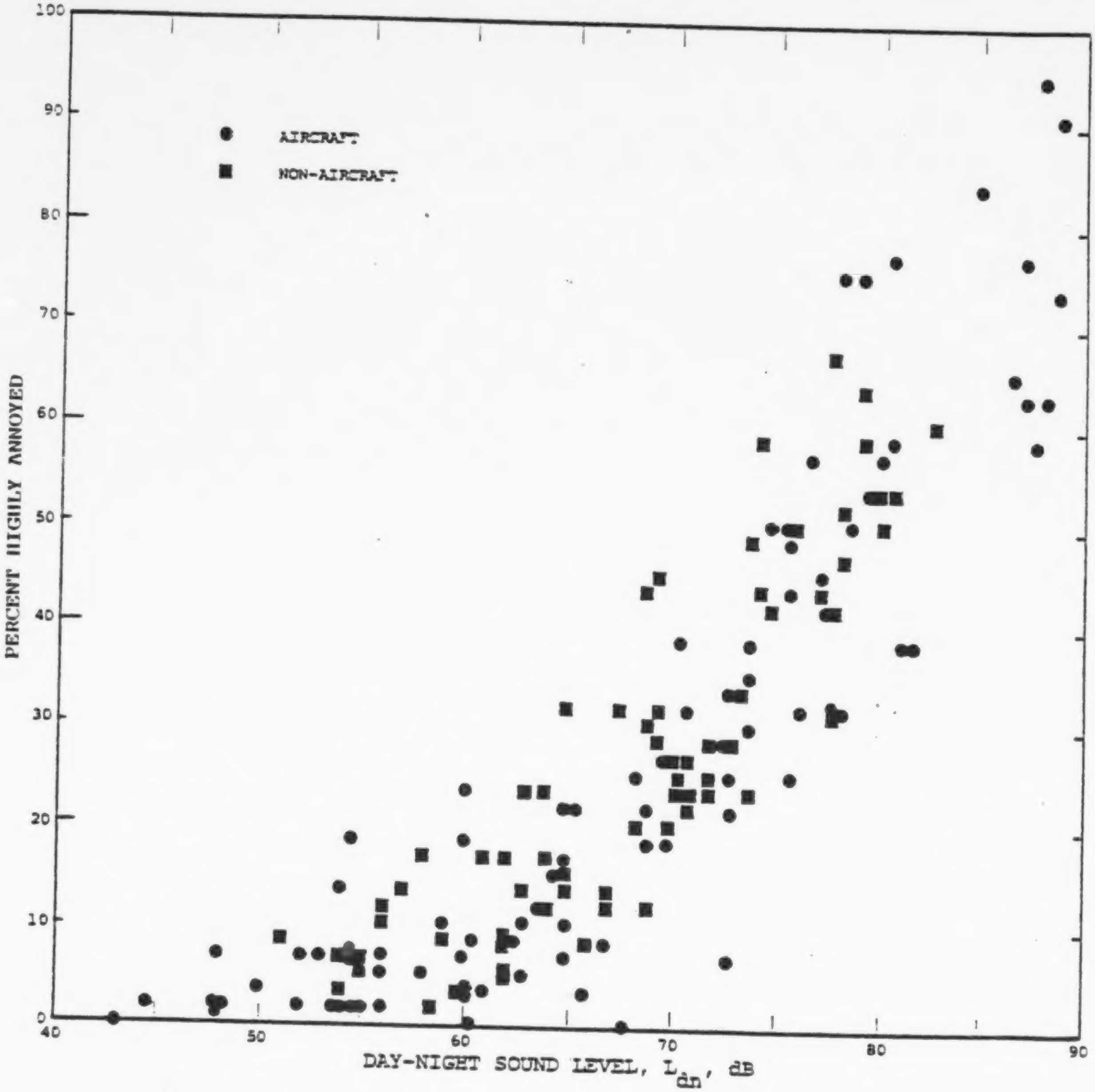

Figure 3-7. PERCENT HIGHLY ANNOYED AS A FUNCTION OF DAY-NIGHT SOUND LEVEL (from Schultz, Reference 67).

1. All aircraft and non-aircraft data points;
2. Aircraft data points only;
3. Non-aircraft data points only (less the French Railroad data).

Linear, quadratic, and cubic functional forms were fitted to each data set. In addition, because of the significant number of data points below L_{dn} of 55* dB, best fit equations were also developed for each data set considering only those points equal to or greater than L_{dn} of 55 dB. However, for this case, only the linear and cubic functional forms were evaluated.

For the aircraft data set only, the best fit relationships derived from all available data points and from data points with L_{dn} equal to or greater than 55 dB are shown in Figures 3-8 and 3-9, respectively. For comparison, the relationship developed by Schultz (as presented in Reference 67) is also shown in each of these figures.

Table 3-6 presents a complete summary listing of the regression equations developed for all survey data sets, functional forms, and the two L_{dn} data point ranges. Additionally, relevant statistics including the standard error of estimate and the product-moment correlation coefficient are presented.

Based on Figures 3-8 and 3-9 and the information presented in Table 3-6, the following conclusions can be made regarding the annoyance response data reported by Schultz [67]:

1. For each of the three data sets considered, there is statistically little difference among the three functional forms used to obtain best fit relationships between percent highly annoyed and L_{dn}. This applies to both L_{dn} data point ranges, i.e., all available data points and only data points with L_{dn} equal to or greater than 55 dB;

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*55 dB has been identified by the EPA as the outdoor yearly day-night sound level that will protect public health and welfare (in residential areas) with a margin of safety.

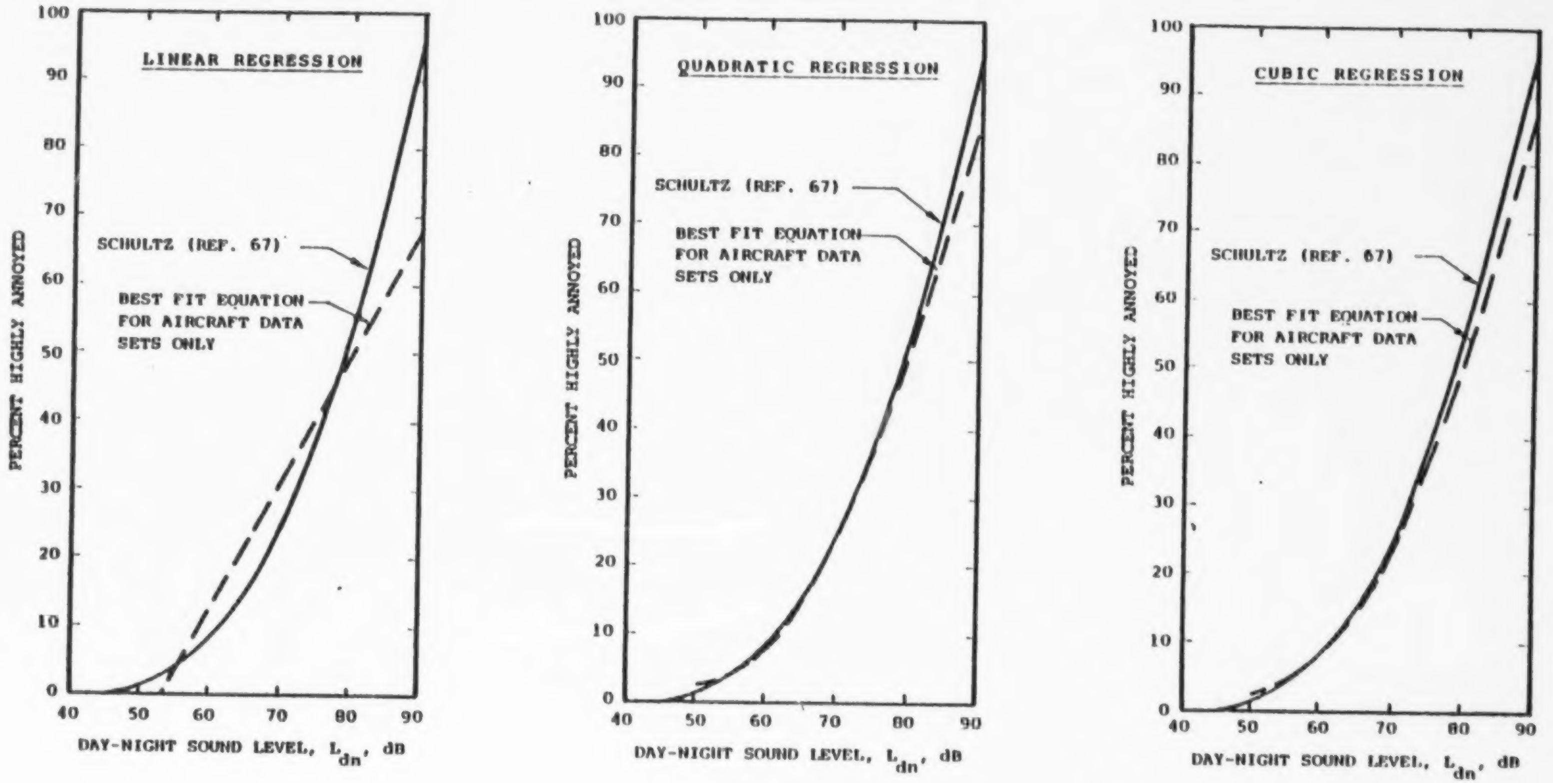

Figure 3-8. PERCENT HIGHLY ANNOYED AS A FUNCTION OF DAY-NIGHT SOUND LEVEL; ALL AVAILABLE DATA POINTS (AIRCRAFT ONLY) USED TO DEVELOP REGRESSION RELATIONSHIPS

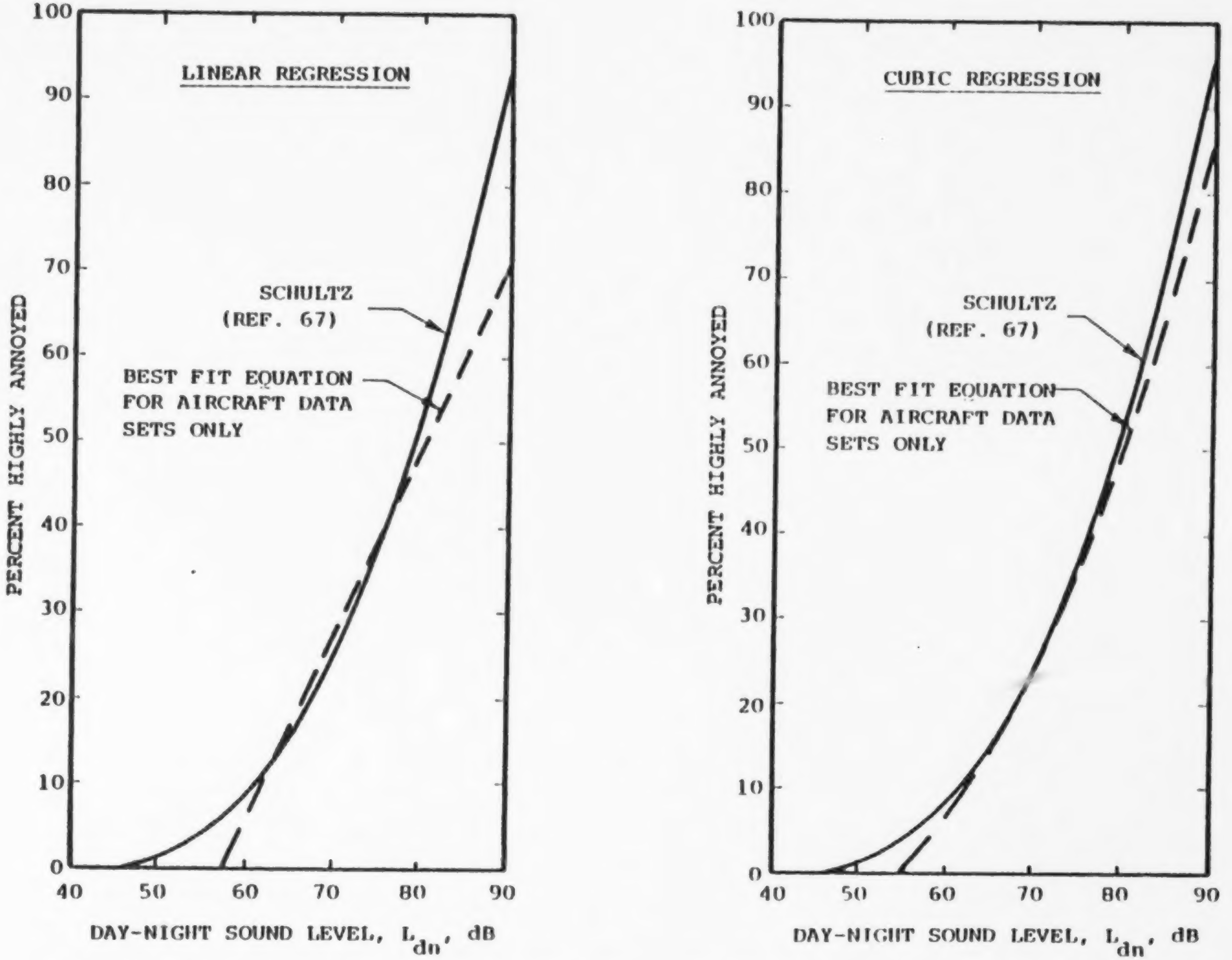

Figure 3-9. PERCENT HIGHLY ANNOYED AS A FUNCTION OF DAY-NIGHT SOUND LEVEL; ONLY DATA POINTS (AIRCRAFT ONLY) WITH L_{dn} EQUAL TO OR GREATER THAN 55 dB USED TO DEVELOP REGRESSION RELATIONSHIPS

Table 3-5 BEST FIT FUNCTIONAL FORMS AND RELEVANT STATISTICAL DATA FOR RELATIONSHIPS REPRESENTING PERCENT HIGHLY ANNOYED (%HA) AS A FUNCTION OF DAY-NIGHT SOUND LEVEL; BASED ON DATA PRESENTED IN REFERENCE 67

FUNCTIONAL FORM	DATA SETS	NO. OF DATA POINTS	ALL AVAILABLE DATA POINTS USED IN REGRESSIONS $\%HA = A + B(L_{dn}) + C(L_{dn})^2 + D(L_{dn})^3$ A	B	C	D	STANDARD ERROR OF ESTIMATE	CORRELATION COEFFICIENT
LINEAR	AIRCRAFT AND NON-AIRCRAFT	155	-99.58	1.86	0	0	10.960	0.870
	AIRCRAFT ONLY	88	-98.26	1.85	0	0	12.294	0.875
	NON-AIRCRAFT ONLY*	62	-105.02	1.94	0	0	8.704	0.875
QUADRATIC	AIRCRAFT AND NON-AIRCRAFT	155	111.92	-4.5628	0.0475736	0	9.234	0.910
	AIRCRAFT ONLY	88	121.24	-4.8647	0.0496931	0	9.950	0.921
	NON-AIRCRAFT ONLY*	62	156.83	-5.9399	0.0584534	0	7.793	0.903
CUBIC	AIRCRAFT AND NON-AIRCRAFT	155	230.21	-10.0340	0.130262	-0.408884×10^{-3}	9.241	0.911
	AIRCRAFT ONLY	88	215.98	-9.2775	0.116643	-0.331349×10^{-3}	9.988	0.922
	NON-AIRCRAFT ONLY*	62	69.24	-2.00021	0 (**)	0.286250×10^{-3}	7.814	0.902

* French Railroad survey data not Included

** Additon of this term did not improve correlation coefficient

Table 3-5 BEST FIT FUNCTIONAL FORMS AND RELEVANT STATISTICAL DATA FOR RELATIONSHIPS REPRESENTING PERCENT HIGHLY (Continued) ANNOYED (%HA) AS A FUNCTION OF DAY-NIGHT SOUND LEVEL, BASED ON DATA PRESENTED IN REFERENCE 67

ONLY DATA POINTS WITH L_{dn} EQUAL TO OR GREATER THAN 55 dB USED IN REGRESSIONS

$$\%HA = A + B(L_{dn}) + C(L_{dn})^2 + D(L_{dn})^3$$

FUNCTIONAL FORM	DATA SETS	NO. OF DATA POINTS	A	B	C	D	STANDARD ERROR OF ESTIMATE	CORRELATION COEFFICIENT
LINEAR	AIRCRAFT AND NON-AIRCRAFT	133	-118.53	2.10	0	0	9.838	0.875
	AIRCRAFT ONLY	69	-124.50	2.17	0	0	10.584	0.886
	NON-AIRCRAFT ONLY*	59	-114.38	2.070	0	0	8.597	0.876
QUADRATIC	AIRCRAFT AND NON-AIRCRAFT	-	-	-	-	-	-	-
	AIRCRAFT ONLY	-	-	-	-	-	-	-
	NON-AIRCRAFT ONLY*	-	-	-	-	-	-	-
CUBIC	AIRCRAFT AND NON-AIRCRAFT	133	14.96	-0.823279	0 (**)	0.189697×10^{-3}	9.741	0.898
	AIRCRAFT ONLY	69	8.54	-0.735085	0 (**)	-0.196373×10^{-3}	10.769	0.908
	NON-AIRCRAFT ONLY*	59	61.98	-1.84365	0 (**)	0.275783×10^{-3}	8.004	0.895

* French Railroad survey data not included

** Addition of this term did not improve correlation coefficient

2. Based on the data used to develop the regression relationships between percent highly annoyed and L_{dn}, it appears that there is little difference between annoyance response to aircraft noise and response to non-aircraft noise sources;

3. The best fit relationships between percent highly annoyed and L_{dn} are generally as good, and in some cases better when data points with L_{dn} less than 55 dB are omitted, i.e., when the "supersensitives" are not considered.

It should be noted that general agreement does not exist concerning the annoyance response similarity between aircraft and non-aircraft noise sources.

In a recent laboratory study* by Rice,[69] sixteen subjects were exposed to aircraft and traffic noise while engaged in a recreational activity. Recordings of the noise produced by Boeing 747's, 707's, 727's, and McDonnell Douglas DC-10's during landing operations were presented to subjects at three A-weighted equivalent of noise levels 40, 50, and 60 dB at three rates of 4, 8, and 16 per twenty-five minutes. Traffic noise was presented at the same noise levels for each of the following three different situations: 1) distant freeway traffic, 2) busy divided highway, and 3) a quiet residential area with trucks. The study results indicated that:

1. Based on average subjective scale values, traffic noise was judged significantly more annoying and more difficult to live with than aircraft noise for equal indoor L_{Aeq} levels.

2. There is no single measure that will predict equal subjective responses for both aircraft and traffic noise.

However, after adjusting for noise reduction (building attenuation),** Rice[69] presents data showing the percent highly annoyed

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*The study was conducted in a simulated domestic living room built within a laboratory environment, and isolated from all noise except that which was deliberately introduced during the coursse of the experiment.

**For aircraft and the distant freeway traffic, the noise reduction was about 20dB, whereas for the divided highway and truck traffic, the loss was closer to 24dB.

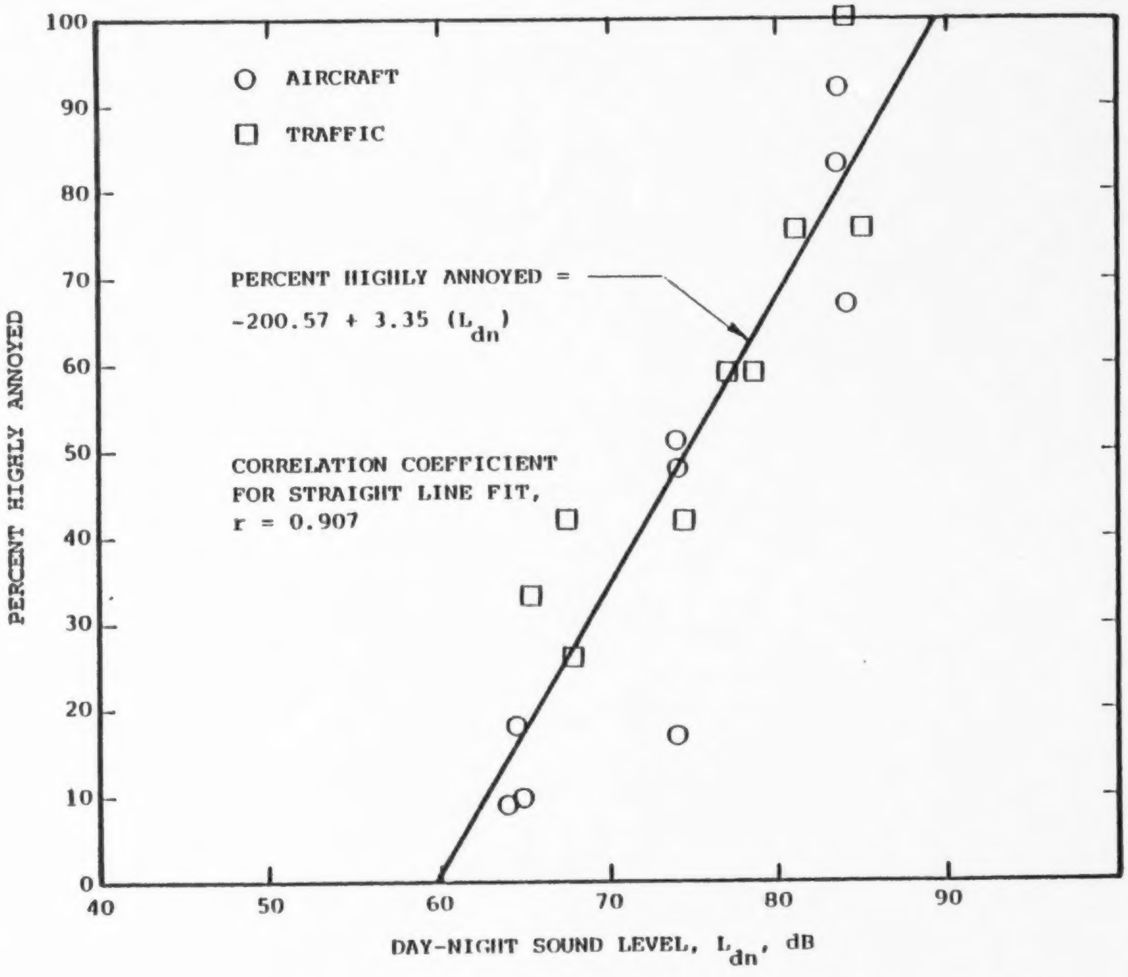

Figure 3-10. PERCENT HIGHLY ANNOYED AS A FUNCTION OF DAY-NIGHT SOUND LEVEL (from Rice, Reference 69).

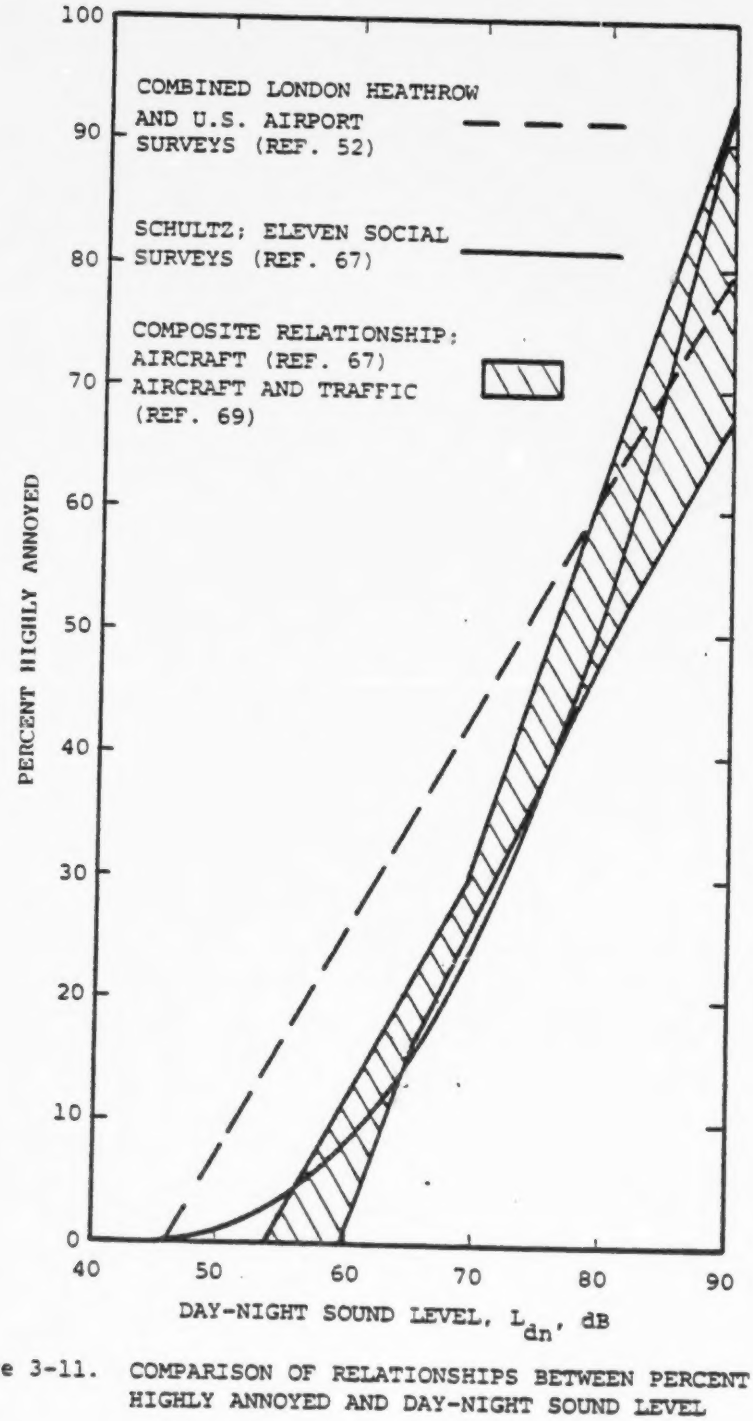

Figure 3-11. COMPARISON OF RELATIONSHIPS BETWEEN PERCENT HIGHLY ANNOYED AND DAY-NIGHT SOUND LEVEL

as a function of outdoor noise level for both aircraft and traffic noise sources. These data, along with a best fit linear relationship, are shown in Figure 3-10. In the development of this relationship, L_{dn} was set equal to L_{Aeq} + 3 dB.* As seen in Figure 3-10, the percent highly annoyed by aircraft noise or by traffic noise, at equal outdoor L_{dn} levels are, for all practical purposes, identical. Although some response differences may exist between the two sources, it would be difficult to conclude that these differences are significant.

Figure 3-11 presents a comparison of a number of suggested relationships between percent highly annoyed and noise exposure levels in terms of L_{dn}. Relationships shown in Figure 3-11 include the following:

1. Combined results of both London-Heathrow Airport surveys and the eight U.S. Airport Surveys (Reference 52),
2. Schultz's generalized relationship based on eleven social surveys (Reference 67);
3. Composite relationship comprised of the following:
   a. Straight-line fits for aircraft data sets (presented in Reference 67) using all available data points and only data points with L_{dn} equal to or greater than 55 dB,
   b. Combined outdoor aircraft noise and traffic noise response data presented by Rice (Reference 69).

With respect to GA aircraft and GA airport operations, relatively little effort has been focused on quantifying community response to noise exposure. Rohrmann[71], Harris,[72,73] and Hall et al.[74] have recently reported results of community survey studies concerning the reactions to noise exposure around airports serving predominantly small, non-commercial aircraft. The results presented in these studies, however, are not sufficient to develop quantitative relationships between percent highly annoyed and level of noise exposure, at least on a basis comparable with other relationships previously shown. Nevertheless,based on the results presented in these recent studies, it is concluded that GA aircraft operations can, and do in some cases, create community noise problems. Rohrmann [71] found that approximately half of those living near the airports investigated are annoyed, to some degree, by aircraft operations. In an investigation involving eight GA airports in Massachusetts, Harris [72,73] concluded that at these airports:

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*This relationship was derived on the basis that the measured difference between the daytime equivalent sound level (L_d) and the nighttime equivalent sound level in typical residential areas is probably on the order of 4 dB (see page B-9 of Reference 70).

1. Cumulative aircraft noise near the ambient resulting from other noise sources resulted in concerted community action;
2. Airport neighbors first complained about levels of noise exposure from touch-and-go training operations about 5 dB lower than they first complained about levels of noise exposure from normal arrivals and departures;
3. Neighbors complained less, for a given noise level, when the neighbors, the FAA and the airport proprietor were able to work together.

Harris[72] suggests noise exposure limits at residentially zoned areas around GA type airports in accordance with the following:

TYPE OF ACTIVITY	NOISE EXPOSURE LIMIT
Itinerant operations	L_{dn} of 55 dB or the annual average of the ambient L_{dn} plus 5 dB, whichever is greater
Touch-and-go operations	L_{dn} of 50 dB or the annual average of the ambient L_{dn}, whichever is greater

Harris[72] also suggests noise exposure limits for areas around commercial (air carrier) airports (L_{dn} of 65 dB) and around airports serving military jet aircraft (L_{dn} of 70 dB). Although the noise exposure limits for GA type airports are from 10 to 20 dB lower than for the other airport types, Harris[72] does not discuss the reasons for these differences.

Hall et al.[74] performed 221 interviews at 15 sites around an airport serving predominantly GA aircraft* to investigate community response to noise from GA airport operations. It was reported that compared with a larger airport serving larger commercial aircraft, lower percentages of speech interference and high annoyance are reported by the GA airport community. However, the GA airport community did report a higher percentage of sleep interference. It was reasoned that the higher percentage of sleep disturbance reported by the GA airport community was probably due to greater noise sensitivity resulting from the infrequent nature of night flights.

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*Aircraft types included the following: 1) executive turbojets, 2) twin-engine propeller, 3) light single-engine propeller (100-200 HP), 4) light single-engine propeller (200-300HP), and 5) twin-engine turboprop.

3.2 Other Dose - Response Relationships

3.2.1 Communication Interference

One of the most obvious effects of noise is its ability to interfere with speech communication. The degree of speech interference, i.e., the masking or disruption of speech, is a function of the type of communication and the conditions under which it must be maintained. Environmental noise may interfere with face-to-face conversations, with telephone use, and with radio and television listening. Noise may also interfere with the ability to hear warning shouts or commands, thus increasing the probability of accidents. Some of the most important factors contributing to speech interference include: 1) the characteristics of the auditory signal to be heard, 2) characteristics of the interferring sound, and 3) separation distance between the source of the auditory signal and the listener. Secondary factors include: 1) acoustical environment in which the communication process takes place, 2) degree of clarity of the auditory signal, 3) hearing acuity of the listener, 4) visual cues, and 5) amount of redundancy in the auditory signal.

The frequency range of speech extends from approximately 100 to 6000 Hz. The total variation in intensity level (dynamic range) of successive sounds is approximately equal to 30 dB. Speech is characterized as an acoustical signal which undergoes rapid fluctuations both in sound level and frequency patterns. The integration and recognition of these constantly shifting patterns is essential for optimum speech intelligibility. Noise not only diminishes the ability to detect the auditory signal, but also reduces a listener's ability to follow the pattern of signal fluctuation. The degree of speech interference is therefore quite sensitive to the level, the energy distribution with respect to frequency, and the temporal characteristics of the interferring sound.

A number of rating schemes have been developed specifically for quantifying the speech interference effects of noise. The most prominent of these are:

- Articulation Index
- Speech Interference Level
- Preferred Speech Interference Level

The Articulation Index (AI) is a numerically calculated measure of the intelligibility of transmitted or processed speech. It takes into account the limitations of the transmission path and background noise. The AI can range in magnitude between 0 to 1.0. AI values of less than 0.1 and above 0.6 represent conditions where the speech intelligibility is generally low and high, respectively. Speech Interference Level (SIL) and Preferred Speech Interference Level (PSIL) are calculated quantities which provide a guide to the interferring effect of noise on reception of speech. The SIL is the arithmetic average of the octave bands in the most important part of the speech frequency range, 600-1200 Hz, 1200-2400 Hz, and 2400-4800. Using octave bands based on preferred frequencies, the PSIL is the arithmetic average taken over the octave band levels centered at 500 Hz, 1000 Hz, and 2000 Hz. A currently proposed measure would also include the octave band centered at 4000 Hz.

An assessment of the rating schemes has been presented by Schultz[15,17] and Yaniv and Flynn[75] and will not be discussed here. However, some important limitations of the use of these rating schemes merits some attention.

The AI method has been used to estimate speech intelligibility in the presence of steady-state and time-varying noise sources. However, use of the AI method for predicting intelligibility of speech in the presence of fluctuating noise levels is questionable. As pointed out by Yaniv and Flynn[75] the AI is based upon, and has been principally validated against, intelligibility tests involving adult male talkers and trained listeners. Thus, the AI cannot be assumed fully applicable to female talkers or children speakers.* Additionally, the complexity of the calculation procedure associated with the AI severely limits its use as a practical means for measuring environmental noise levels.

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*In a recent study by Pearsons et al.[76] it was found that for the speech categories of: 1) normal, 2) raised, and 3) loud, minimal voice level differences existed between male, female, and children speakers. However, it was found that male speakers show a greater concentration of energy in the one-third octave bands below 200 Hz.

The principal limitations of the SIL and PSIL procedures are: 1) neither is very appropriate for evaluating the speech-interferring effects of noise with considerably more energy at high frequencies than at low frequencies, and 2) neither accurately measures the masking of speech by noise containing intense low frequency components.

Figure 3-12 shows the relationship between speaker-listener separation distance as a function of AI for normal vocal effort and ambient noise level (given in terms of SIL, PSIL (0.5, 1, 2 kHz), L_{PN}, and L_A) and as a function of various vocal efforts and ambient noise levels.

A number of studies related to the speech interference effects of aircraft flyover noise have been reviewed. Using word intelligibility tests, Kryter and Williams[77] investigated the speech interference effects of recorded "run-up" and flyover noise from jet (turbojet and turbofan) and propellerdriven aircraft.* Half of the intelligibility tests were administered with the noise filtered to achieve indoor spectra and levels. The speech levels selected were 80 dB, 84 dB, and 88 dB for the outdoor test condition and 65 dB, 69 dB, and 73 dB for the indoor test condition. A number of rating schemes were used as a means of evaluating and validating the speech interference effectiveness of the aircraft noise. Some of these rating schemes included L_P, L_C, L_A, SIL, AI, and L_{PN}. It was reported that:

1. The speech interference effects of the noise from jet and propeller-driven aircraft cannot be adequately evaluated from L_C or L_A measures;
2. SIL or L_{PN} calculated by either the full- or 1/3-octave band methods, provide moderately accurate methods of estimating the speech interference effects of aircraft noise;
3. The AI calculated by either the full- or 1/3-octave band methods predicts with reasonable accuracy the understandability of speech in the presence of the aircraft noises used in the study;

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* Aircraft types were: 707-120, 720B, 727, and a Super-Constellation.

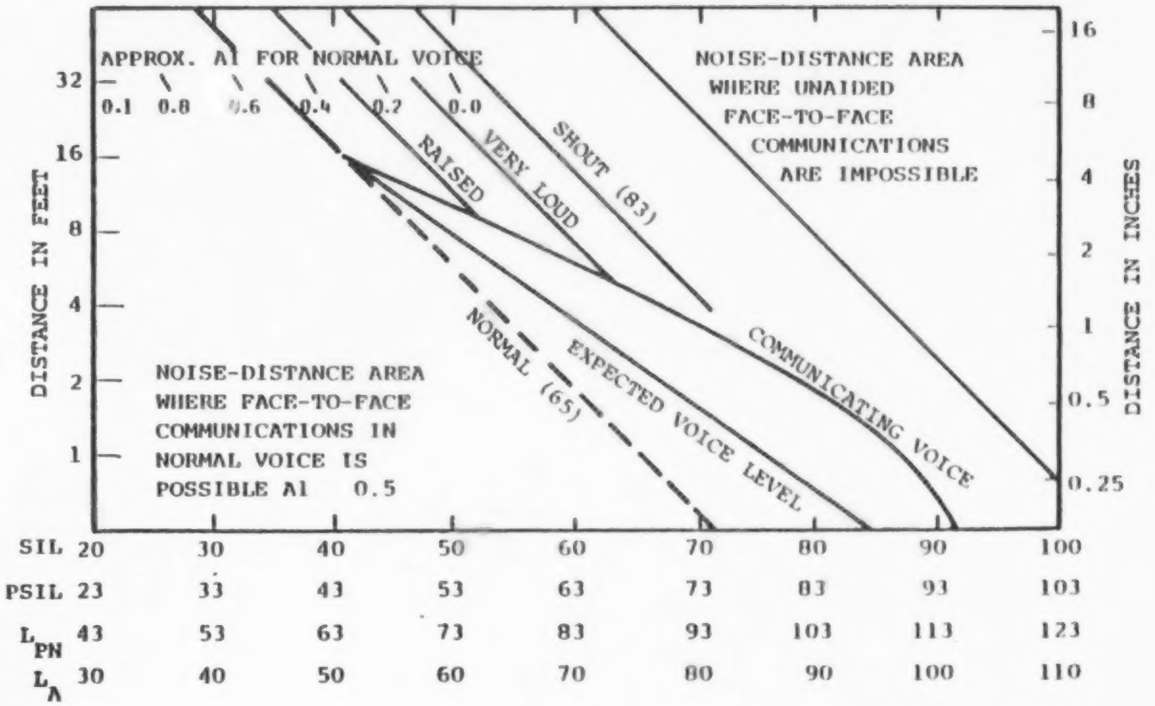

Figure 3-12. REQUIRED DISTANCE BETWEEN SPEAKER AND LISTENER FOR SATISFACTORY FACE-TO-FACE COMMUNICATION AS A FUNCTION OF AI FOR NORMAL VOCAL EFFORT AND AMBIENT NOISE LEVEL AND AS A FUNCTION OF VARIOUS VOCAL EFFORTS AND AMBIENT NOISE LEVELS (from Reference 79).

4. The full- or 1/3-octave band methods of calculating either L_{PN} or AI gave essentially the same results for the noise conditions tested in the study. However, the 1/3-octave band method should be generally more reliable and accurate than the full-octave band method when applied to a wider variety of aircraft noises.

In a later study, Williams et al.[20,78] conducted an investigation to determine the extent that simulation of speech activities influence the acceptability of single flyover noise. Until this investigation, most psychoacoustic laboratory studies had been performed in which the only task that was required of subjects was to rate the individual flyover noises. However, this was thought to be unrealistic since in a real-life situations, flyover noise from aircraft intrudes upon ongoing activites, particularly those involving communication.

Acceptability ratings were obtained under the following three experimental conditions:

1. 35 flyovers ranging from 63 to 83 L_{pmax} with no speech signal presented;
2. 45 flyovers ranging from 63 to 93 L_{pmax} with simulated radio-TV listening;
3. 35 flyovers ranging from 63 to 83 L_{pmax} with simulated telephone listening.

For the second experimental condition, the 10 additional flyovers were presented along with speech monitoring levels of 71 and 83 dB. Twenty-six college students served as subjects and their task was to rate the single-event flyover intrusions on a four-point adjectival category scale. The scale used was: (1) of no concern, (2) acceptable, (3) barely acceptable, and (4) unacceptable.

For the two speech conditions, i.e., with radio-TV listening and telephone listening, subjects answered written questions concerning the contextual speech message. The flyover noises presented were evaluated utilizing L_{PNmax}, L_A, and SIL and related to the judgment results.

Results and conclusions were:

1. For comfortable radio and TV listening (a level corresponding to that measured at a distance of about one meter from a talker speaking in a raised voice), there is a sharp drop in estimated sentence intelligibility when the peak noise level value of an aircraft flyover exceeds a perceived noise level of about 88 dB, a SIL of 68 dB, or an A-weighted sound level of 76 dB; such a peak noise level also results in an appreciable deterioration in comprehension of verbal messages of the type that might be presented in a radio or TV news broadcast; an aircraft flyover with this peak level is rated by listeners to be "barely acceptable," if it is assumed that such a flyover will occur a number of times during a day;

2. The relationship between acceptability ratings of aircraft noise and various physical measures of the peak noise levels are essentially the same whether the ratings are obtained in the absence of speech or with speech present at a comfortable listening level (radio-TV speech or telephone speech); this finding indicates that no correlation factors need to be added to, or considered with, L_{PN} values to achieve estimates of the acceptability of aircraft noise in terms of both perceived noisiness and speech interference; this finding also suggests that procedures based on speech interference might be equally as effective in estimating the acceptability of aircraft noise as procedures based on perceived noisiness;

3. When aircraft noises are rated in the presence of speech, an increase or decrease in speech level results in an increase or decrease in acceptability;

4. Correlations between listener ratings of acceptability and various physical measures of peak aircraft noise L_{PN}, SIL, and L_A are essentially the same, indicating that any one of these three measures is equally effective for predicting listener acceptability;

5. The mean of the differences between "acceptable" and "unacceptable" for the three conditions was 22 dB (A-weighted sound level);

6. The mean of the L_A ratings for "acceptable" was approximately 64 dB indicating that most persons would find this peak level acceptable.

In the EPA Airport/Aircraft Noise Study,[70] it was reported that two meters was a typical outdoor coomunication distance in urban areas. In order to permit 95 percent sentence intelligibility at this distance using normal voice effort, it was determined that steady, continuous A-weighted background sound levels cannot exceed 60 dB. This level was recommended as the maximum permissible value for intruding steady noise for speech communications outdoors. Since the magnitude of almost all environmental noises fluctuates over time, this maximum permissible level was interpreted as an average or equivalent-continuous level (L_{eq}). For indoor environments, an A-weighted L_{eq} level of 45 dB was identified as the maximum permissible value which would assure 100 percent sentence intelligibility for relaxed conversation. It was pointed out that speech interference criteria based on average or equivalent-continuous sound level measures are best applied to environmental noises which are steady. However, average sound level measures are conservative when applied to non-steady noises, when maximum levels do not cause a complete interruption of speech communication. However, when maximum levels are sufficient to cause complete interruption of speech communication, a situation which often occurs with aircraft flyovers, annoyance criteria are probably more applicable in assessing human response than speech criteria given in terms of percentage of sentence interference.

For residential areas, the EPA "Levels Document"[52] identified L_{dn} values of 55 dB and 45 dB as the maximum permissible levels of intruding noise to allow satisfactory speech communication in outdoor and indoor noise environments, respectively. It was reported that below these levels, no effects on "public health and welfare" would occur as a result of interference with speech. Although the outdoor maximum permissible level identified in the "Levels Document" is 5 dB lower than that recommended in the earlier EPA Airport/Aircraft Noise Study (assuming L_{dn} to be approximately equal to $L_{eq(day)}$ + 3 dB), it was reported that the additional 5 dB would significantly increase the average community noise exposure response from approximately 17 percent to 23 percent highly annoyed. Based on data presented in the EPA "Levels Document", Figures 3-13 and 3-14 present relationships between A-weighted equivalent-continuous sound level and percent sentence unintelligibility for indoor and outdoor noise environments, respectively.

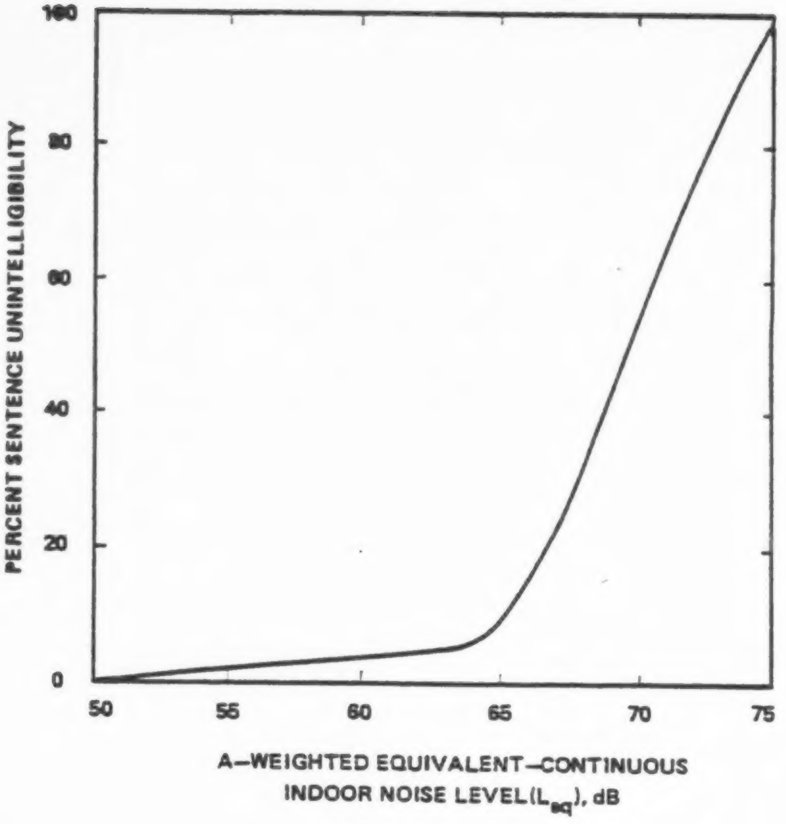

FIGURE 3—13 PERCENT SENTENCE UNINTELLIGIBILITY AS A FUNCTION OF A—WEIGHTED EQUIVALENT—CONTINUOUS INDOOR NOISE LEVEL; NORMAL VOICE AT 2 METERS (EPA "LEVELS DOCUMENT" , REFERENCE 52).

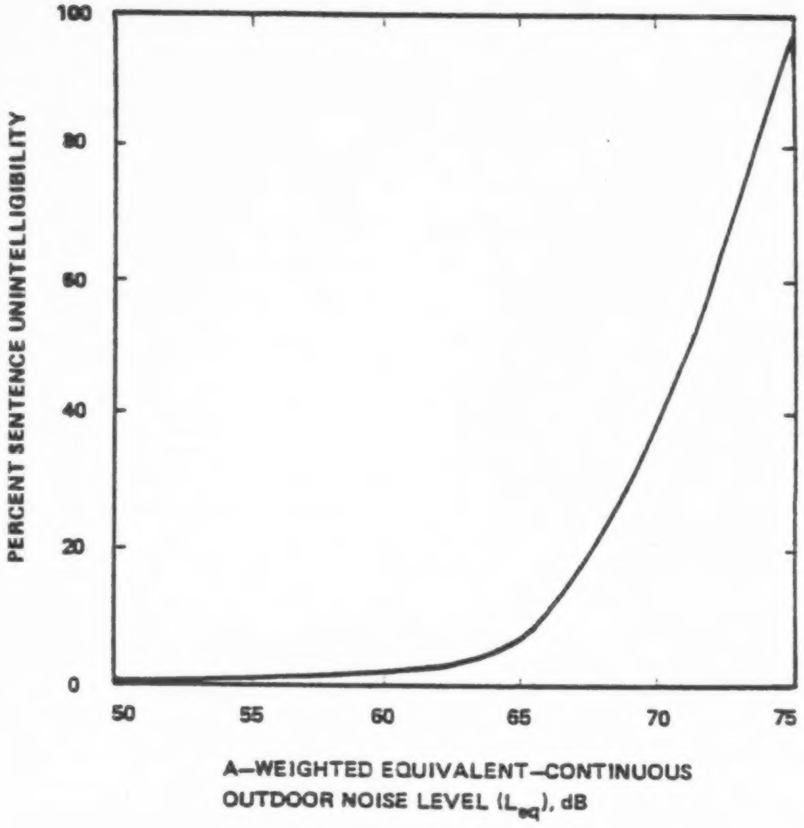

FIGURE 3—14. PERCENT SENTENCE UNINTELLIGIBILITY AS A FUNCTION OF A—WEIGHTED EQUIVALENT—CONTINUOUS OUTDOOR NOISE LEVEL; RELAXED CONVERSATION AT GREATER THAN 1 METER SEPARATION, 45 dB BACKGROUND IN THE ABSENCE OF INTERFERING NOISE. (EPA "LEVELS DOCUMENT", REFERENCE 52)

3.2.2 Noise-Induced Hearing Loss

Exposure to noise of sufficient intensity for sufficiently long periods of time results in a temporary increase of the threshold of audibility, i.e., Temporary Threshold Shift (TTS). This loss usually can be regained in approximately 16 hours after the noise exposure terminates. Repeated exposures to high intensity noise levels which cause large TTS, will eventually lead to irreversible, permanent loss of hearing, i.e., Noise-Induced Permanent Threshold Shift (NIPTS).

It has been found that regular exposure to A-weighted sound levels of from 60 to 80 dB for periods in excess of 8 hours will cause some TTS in a significant proportion of the population exposed. Noise from 1000 to 6000 Hz appears to cause the greatest TTS with noise-induced hearing loss initially occurring at approximately 4000 Hz.

It is generally agreed that for a given L_{eq}, intermittent or time-vary noise will produce less hearing damage than a continuous noise with the same acoustical energy. In order to make a reasonable assessment of the potential hearing damage resulting from exposure to time-varying noise, a number of concepts have been proposed to define the trading relationship between exposure time and noise level. Two methdologies which have been used extensively to assess hearing damage potential are the TTS and the equal-energy concepts. Briefly, the TTS concept states that a TTS measured 2 minutes after cessation of a 8-hour noise exposure closely approximates the NIPTS incurred after a 10 to 20 year exposure to that same level. The equal-energy concept states that equal amounts of sound energy will cause equal amounts of NIPTS regardless of the distribution of the energy across time. Neither concept has been shown to be applicable to all noise exposures as is pointed out by a number of studies which have examined the uses and limitations of both methodologies. Nevertheless, the equal-energy concept has been selected by the EPA on the basis that it is a reasonable predictor of TTS and that it tends to be conservative with respect to the observed characteristics of environmental noise over a 24-hour time period.

Only a few studies have attempted to directly relate actual community aircraft noise exposure to noise-induced hearing loss. Parnell et al.[80] investigated the effects of aircraft noise on the hearing of residents in communities surrounding Los Angeles International Airport. Investigation results indicated that at the higher audible frequencies there were trends which suggested poorer hearing for the airport community as compared with an aircraft-noise-free community. However, it was reported that because of the uncertainties in the study results, the apparent poorer hearing of the airport community residents could not be conclusively linked to aircraft noise exposure.

Recently, Ward et al.[81] attempted to determine the auditory threshold shift of subjects exposured to peak A-weighted noise levels of 111 dB produced by recorded commercial jet aircraft (DC-8 and 720-B) flyovers. Six-hour exposures to landings and takeoffs at the rate of 1 per 1.5 or 3 minutes were administered to two groups of five normal listeners. TTS was determined by measuring auditory thresholds at three frequencies in both ears after 1, 2, 4 and 6 hours of exposure and at three other frequencies after 5 hours and comparing these with pre-exposure thresholds. Recovery was followed by testing at 15 minute intervals for 2 hours after the last flyover and again 16 hours after exposure. The mean TTS_2 (temporary threshold shift 2 minutes after exposure) did not reach 5 dB at any frequency for either exposure condition. Ward et al.[81] concludes that the possibility of suffering a measureable permanent loss of hearing as a result of aircraft flyovers in a residential neighborhood is remote, even for persons who live immediately adjacent to a busy airport.

Hiramatsu et al.[82] investigated the TTS due to recorded takeoffs with peak A-weighted levels of from 75 to 100 dB. The acoustical energy in the noise signal was concentrated primarily in the frequency range of from 500 to 4000 Hz. Five normal listeners were exposed to flyovers at a rate of 1 per 2 or 4 minutes for about 9 hours at a time. TTS measurements were made 0.5 minutes after cessation of the noise exposure at various intervals of the total exposure time duration. All TTS measurements reported were the average TTS at 4000 Hz obtained from all five subjects. Results indicated that the growth of TTS at 4000 H_z is approximately expressed as a function of $Log_{10}T$, where T is the exposure time in minutes. Based on the study results, Hiramatsu et al.[82] reported that exposures to peak A-weighted levels of 75 dB at a rate of 1 per 2 minutes did not produce TTS significantly different from the TTS for a non-exposure condition, and that growth of TTS does not begin until peak A-weighted levels are between 75 and 80 dB.

The EPA Airport/Aircraft Noise Study[70] presents data which show that the maximum NIPTS produced in a population after forty years of noise exposure (after the age of twenty) is more severe for 4000 Hz than the average of the traditional speech frequencies of 500, 1000, and 2000 Hz. As a result of this finding, a significant proportion of the existing hearing - loss criteria has been based on the avoidance of any substantial loss of hearing at 4000 Hz. Additionally, it has been found that a 5 dB NIPTS variation in an individual's threshold of hearing is generally considered as normal. Based on a 4 dB difference between outdoor day and night average sound levels, and on 8 hours of outdoor exposure to intermittent noise, resulting in an A-weighted continuous-equivalent sound level of 80 dB*, it was concluded that L_{dn} of 83 dB or less will produce no noticeable hearing change over the 500 to 4000 Hz range in 90 percent of the population. Due to the uncertainties associated with some of the assumptions made in deriving the maximum permissible level, it was recommended that a yearly outdoor L_{dn} of 80 dB be used as the noise exposure limit to protect against hearing loss from aircraft noise.

Taking into account that 4000 Hz is the most sensitive to hearing loss and that losses of less than 5 dB are generally not considered noticable or significant, the EPA "Levels Document"[52] identified an 8-hour exposure level not exceeding 75 dB, or a 24-hour exposure level not exceeding 70 dB as requisite to protect 96 percent of the population from greater than a 5 dB NIPTS. This recommendation was based on exposure to steady noise of 8 hours per day, 5 days per week, over a period of 40 years. Figure 3-15 presents curves showing the maximum and average noise-induced permanent threshold shift expected after a 40-year exposure (from

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*This level and duration of noise exposure will produce a NIPTS at 4000 Hz of 6 dB (A-weighted) in the most sensitive 10 percent of the population after 40 years of daily exposure.

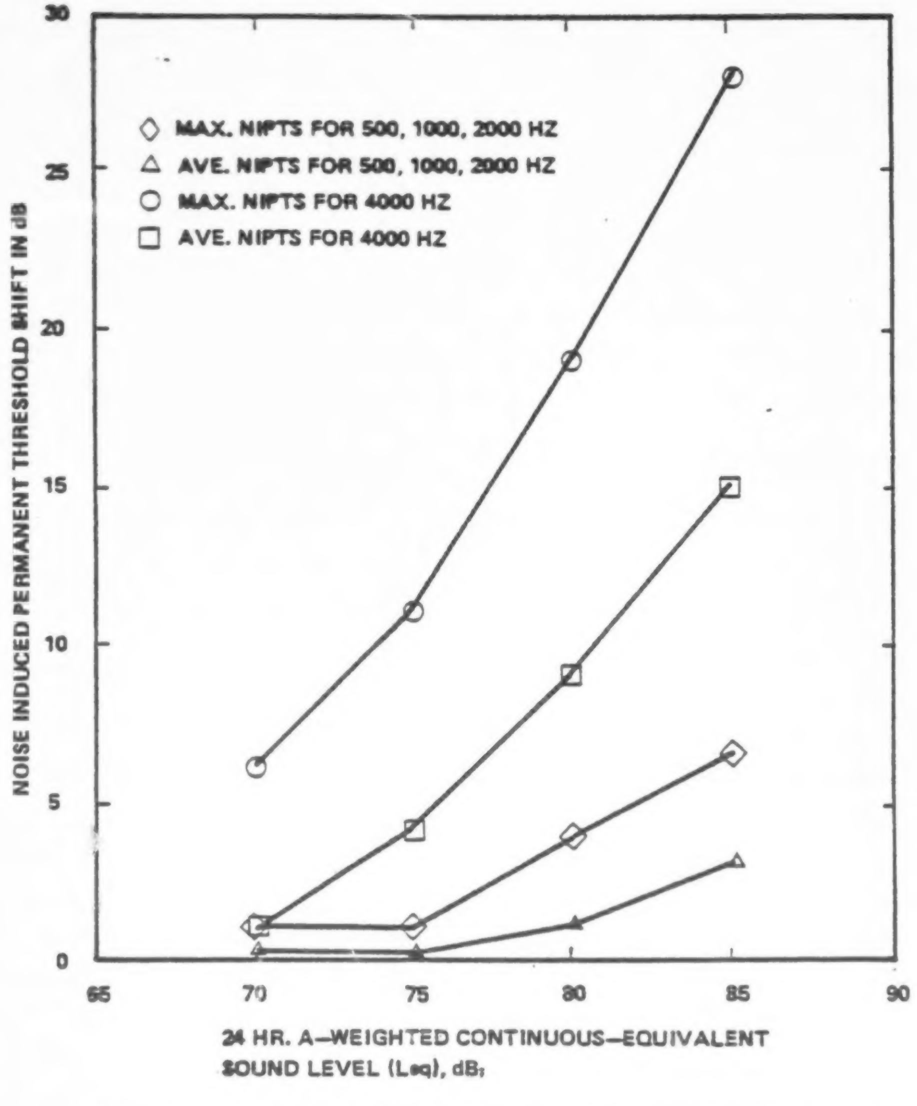

FIGURE 3–15. AVERAGE NOISE–INDUCED PERMANENT THRESHOLD SHIFT (NIPTS) (BEYOND PRESBYCUSIC LOSSES) EXPECTED AS A FUNCTION OF A–WEIGHTED CONTINUOUS–EQUIVALENT SOUND LEVEL (DEVELOPED FROM DATA PRESENTED IN EPA "LEVELS DOCUMENT", REFERENCE 52)

age 20 to 60 years) to a 24-hour A-weighted continuous-equivalent level. The curves shown in Figure 3-15 were developed from data presented the EPA "Levels Document".

3.2.3 Sleep Disturbance

Sleep is not one continuous or uniform condition. It is a complex series of states through which the brain progresses in a cyclic pattern, repeated several times over the course of the sleeping period. Although there are no sharp distinctions between different states, it is generally agreed that there are basically five stages of sleep. Each stage is identified by specific patterns of frequency and amplitude combinations which are typically observed from electroencephalogram*(EEG) recordings. Laboratory investigations have shown that noise can effect changes or shifts in sleep stages without actually causing a sleeper to awaken as well as producing arousal or behavioral awakening. Arousal is defined as the response which results in an EEG pattern having some or all of the characteristics of an awake EEG, while behavioral awakening requires a specific motor or verbal response.[83] The principal factors which have been found to affect responses to noise during sleep include: 1) age, 2) sex, 3) sleep stage, 4) noise level, 5) frequency of noise occurrence, 6) noise quality, and 7) presleep activity. Due to the extreme behavioral and physiological differences among individuals, and the suspected effects of habituation and adaptation to noise exposure during sleep, few studies have attempted to describe the effects of noise in a way which can be used to establish criterion levels. Those studies which have presented quantitative stimulus-response relationships have focused attention on sleep pattern disruption and awakening responses rather than the short- and long-term after effects such as psychological and physiological disorders, or task performance degradation during periods following sleep disturbance.

In terms of aircraft noise effects, a number of relevant studies have been performed (e.g., LeVere[84], Lukas et al.[85], Borsky[60] and Lukas[83,86,87]). LeVere[84] conducted an investigation to assess the arousal produced by the occurrence of noise from jet aircraft flyovers (Boeing 707) and by different auditory frequencies which were equated for subjective but not physical intensity. The aircraft noise was presented to six male subjects on randomly selected nights over a 14 day period. Nine flyovers were presented each night, lasting approximately 20 seconds and reaching a maximum A-weighted sound level of approximately 80 dB. The results indicated that broad-band auditory stimuli will reliably produce arousal and that this arousal appears to outlast the physcial presence of the stimulus by at least a period of 5 minutes.

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*An EEG is a graphical recording of the variations in potential between electrodes adhered to the outside of the head.

The different auditory frequencies were presented to eight male subjects on three nights over a 4 day period. Sounds consisted of 20 presentations of one-third octave band sound centered on a frequency of 125 Hz, 250 Hz, or 1000 Hz, all equated for loudness to an A-weighted sound level of 80 dB. Results showed that all frequencies were effective in producing arousal in sleeping subjects but they were not always equally effective as would be predicted on the basis of their psychological loudness. LeVere[84] concluded that the effectiveness of different frequencies in their arousal capacities was not predictable on the basis of the L_A approximation of equal loudness.

Lukas[86] summarized five years of work at the Stanford Research Institute which pertained to the investigation of test subject and stimulus variables that appeared to be the major determinants of human response to sub-sonic and supersonic aircraft noises during sleep. The summarized results of these studies suggest that:

1. Children 5-8 years of age are uniformly unaffected by noise during sleep;
2. Older subjects are more sensitive to noise than are younger subjects;
3. Women are more sensitive to noise during sleep than men;
4. Within their age group, individuals may vary greatly with respect to their relative sensitivities to noise during sleep;
5. The frequency of behavioral awakening is a function of the intensity of the sub-sonic jet flyover noise. As stimulus intensity increases, the frequency of behavioral awakening also increases, and the frequency of no discernible EEG change decreases.

In a later study, Lukas[83,87] conducted a comprehensive review of domestic and foreign scientific literature on the effects of noise on human sleep. Lukas[83,87] concluded that available data indicate that a reasonably accurate prediction of the frequency of sleep disruption can be made if the noise is described in terms of single-event measures which account for its spectral characteristics and its duration. L_{EPN} appeared to be slightly more accurate than either EL_A or SENEL. Maximum L_A or L_{PN} are far less accurate than either of the measures which account for duration. Additionally, it was reported that overall sleep quality* can be predicted with reasonable accuracy from multiple-event measures such as CNR, when they are calculated using EL_A or L_{EPN} as the basic single-event measure. Relationships between frequency of sleep disruption and noise level, and frequency of arousal or behavioral awakening and noise level were developed from the data presented by Lukas[83]. Approximate mathematical expressions for these relationships are given by:

$$FSD = 1.40\ L_{EPN} - 74.00 \qquad (3\text{-}8)$$

and

$$FABA = 1.03\ L_{EPN} - 58.90 \qquad (3\text{-}9)$$

where FSD is the frequency of sleep disruption and FABA is the frequency of arousal or behavioral awakening. It should be noted that the L_{EPN} used in equations 3-8 and 3-9 was calculated using the time interval between the 10-dB downpoints of the noise signal as the effective duration and using 0.5 seconds as the reference duration.

Thiessen[88] has recently presented the results of an investigation to determine the probability of disturbance of sleep, as judged by EEG records, by seven noises per night produced by a recording of a passing truck. Responses were measured in terms of sleep disruption (defined as sleep stage shifts from deeper to shallower) and behavioral awakenings as a function of peak A-weighted sound level. Thirty-five subjects ranging in age from 16 to 77 years of age (12 between ages of

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*Sleep quality is measured in terms of: 1) feelings of well being on arousal, 2) feelings about the general quality of sleep, and 3) an estimate of how long it took to fall asleep.

16-28, 8 males and 4 females; 12 between ages of 46-51, 7 males, 5 females; and 11 between ages 55-75, all male) were exposured to peak levels of 35 to 75 dB over a period of 24 successive nights. It was concluded that:

1. Young and old people have nearly the same response to noise while middle-aged subjects are more sensitive by about 15 dB;
2. The stimulus-response relationship can be roughly approximated by a linear relationship between response and peak A-weighted level;
3. The probability of shifts in sleep to a shallower level does not appear to adapt in 24 successive nights with seven noises per night, but the probability of waking drops to half value in about two weeks;
4. Response increases with duration of the noise, at least over the limited range of from fractions of a second to a minute.

Additionally, Thiessen[88] compared the stimulus-response relationships derived from average response data (averaged over all ages) for sleep disruption (shifts in sleep stage) and behavioral awakenings with the data given by Lukas[87] in an earlier study. Thiessen[88] reported that the regression line representing the probability of awakening was a reasonable fit to Lukas' data except that the slope appeared to be too low. Also, the regression line representing the probability of sleep disruption was in good agreement with the data from Lukas[87], but was shifted about 10 dB or more to the left, suggesting greater sensitivity by that amount. It should be noted that although no relationship between L_{EPN} (as defined by Lukas[83]) and L_{Amax} was reported by Thiessen[88], examination of the data presented shows that the maximum A-weighted levels were converted to approximate L_{EPN} values using the relatipnship $L_{EPN} = L_{Amax} + 21$. This approximate relationship between L_{EPN} and L_{Amax} is also supported by data reported by Lukas.[83]*

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*Using data presented in Table I. of Reference 83, the average difference between L_{EPN} and L_{Amax} was 20.8 dB.

Most recently, Griefahn and Muzet[89] have presented the results of a literature search concerning the effects of noise-induced sleep disturbances. The stimulus-response relationships were given in terms of percent of awakenings and in terms of percent of O-reactions (defined as all reactions less than a change of one sleep stage) as a function of maximum A-weighted level. The following general conclusions regarding the characteristics of the noise were reported:

1. Bandwidth - Sleep disturbances are greater with increasing bandwidth;
2. Number of Stimuli Per Night - A noise of moderate peak intensity occurring regularly is less disturbing than the same noise occurring randomly.
3. Duration of Noise Exposure - Habituation to noise during sleep depends on the information content of the noise and on motivation. Habituation for autonomic responses has not been demonstrated.

Additionally, it was reported that with increasing age, the probability of awakening reactions becomes greater, whereas the probability of O-reactions becomes less. Differences in the reactions of female and male subjects is not clear since results for different laboratory experiments are contradictory.

For comparison, the stimulus-response relationships concerning the probability of awakening and the probability of sleep disruption presented by Lukas[83], Thiessen[88], and Griefahn and Muzet[89] are shown in Figures 3-16 and 3-17. The relationships are given in terms L_{EPN} (as defined by Lukas[83]) assuming a 21 dB difference between L_{EPN} and L_{Amax}, i.e., $L_{EPN} = L_{Amax} + 21$.

3.2.4 Nonauditory Physiological Effects

In the physiological response area, the results of human and animal experiments show that average or intrusive noise can act as a stress-provoking stimulus.[90] The autonomic nervous system (sympathetic and parasympathetic) responds to stressful agents (such as noise) and tries to regulate the perturbation in bodily functions by effecting

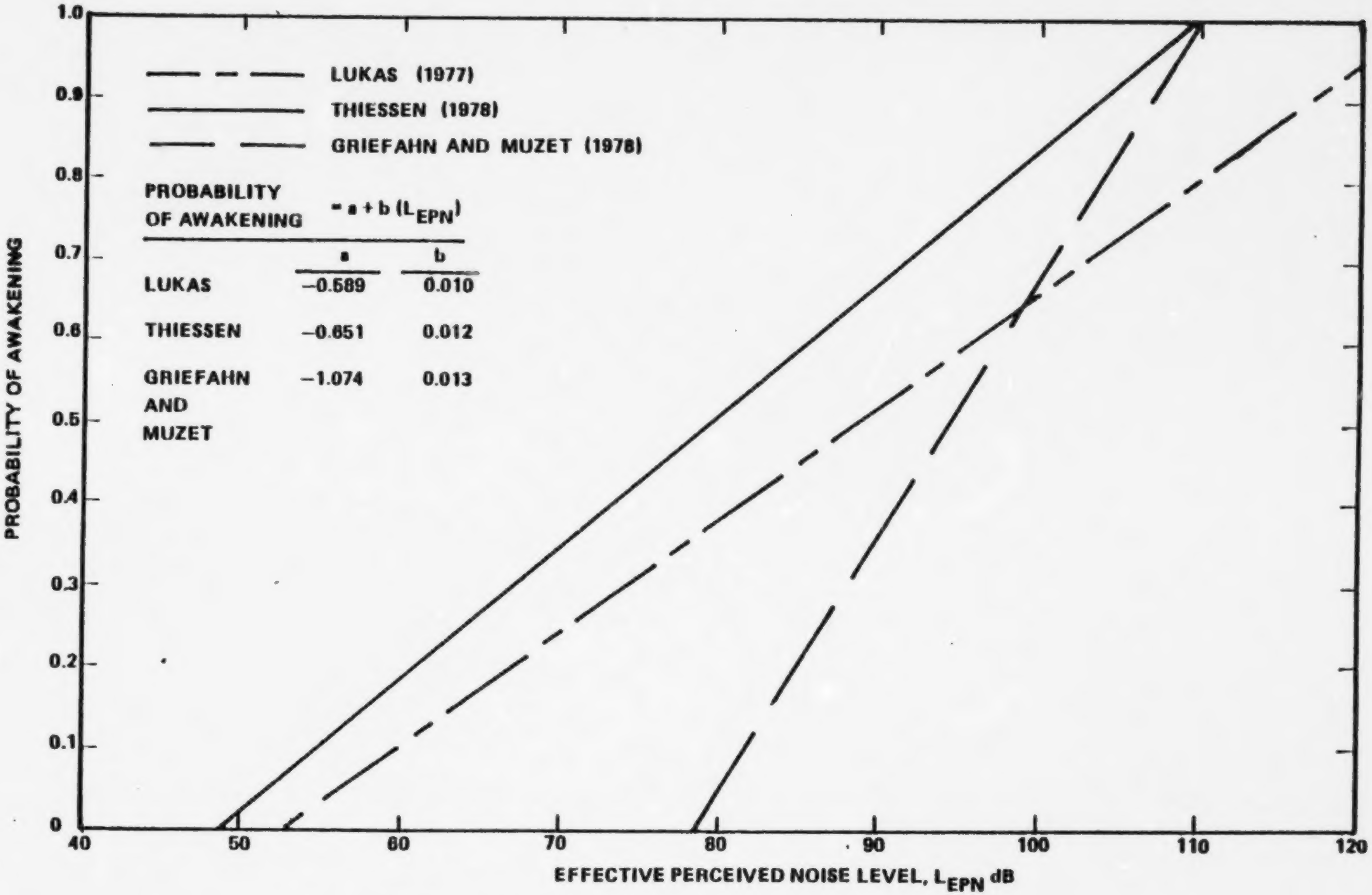

FIGURE 3–16. PROBABILITY OF AWAKENING AS A FUNCTION OF NOISE STIMULUS IN TERMS OF L_{EPN}

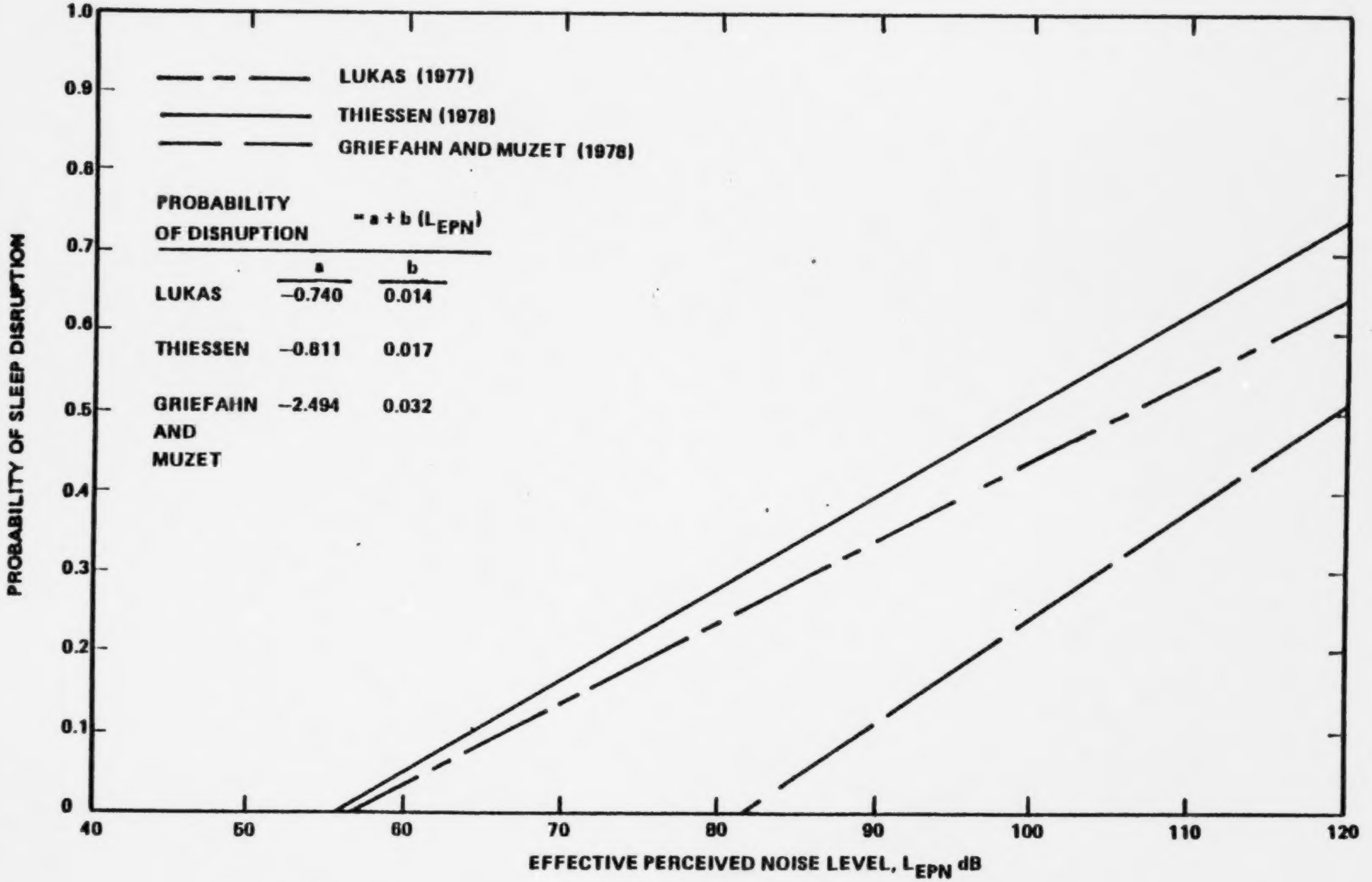

FIGURE 3–17. PROBABILITY OF SLEEP DISRUPTION AS A FUNCTION OF NOISE STIMULUS IN TERMS OF L_{EPN}

changes in circulatory, respiratory, excretory, and glandular organs. For longer term noise exposures the result may be the chronic stress syndrome. Stress is known to be a factor in the development of peptic ulcers, cardiovascular disease (hypertension and coronary artery disease), and is suspected to be a factor in the aging process.

Increased blood pressure (generally considered an adverse health effect) and its attendant effects have been observed both for short-term environmental noise exposures, and longer-term occupational noise exposures.[90] In the case of noise exposure in the earlier stages, a study of school children exposed to noise from heavy street traffic (1000 cars/hour) showed that they had considerbly higher blood pressure than children from schools in quieter areas (traffic rate at 50 cars/hour).[91]

Several studies of workers exposed to high noise levels have indicated chronically elevated blood pressure, and peripheral circulatory and cardiovascular problems. Workers chronically exposed to A-weighted noise levels in the 90 to 96 dB range exhibited significantly greater incidence (3 to 4 times the normal rate) of hypertension.[90] Additionally, industrial workers with hearing impairment (thus long-term high level noise exposure) had a 3 times greater rate of hypertension compared to industrial workers with no significant hearing loss.[92] The evidence thus indicates that stress reactions due to noise exposure cause higher than normal blood pressure (a persistent response), and that repeated and prolonged noise exposure may be a contributing factor to chronic or acute hypertension, and other cardiovascular problems. Thus, noise-induced stress may not necessarily manifest itself only in hearing damage or fatigue. As an additional example, health data from the U.S.S.R. indicate that changes in general morbidity and its character in populations living in noisy areas of big cities can definitely be correlated with noise levels.[93]

Other noise stress tests in which physiological response was measured have been conducted in laboratory studies using continuous and intermittent tones and recorded aircraft noise. The results indicated that intermittent noise had a stronger effect than continuous noise on the nervous system and cardiovascular functioning.[94] Thus, the total noise exposure time may not be as important an indicator of nonauditory physiological effects as the pattern or combination of noise exposure and quiet periods. In a test using recorded jet noise, a continuous noise exposure equivalent to 120 aircraft at $L_{Amax} = 87$ dB induced sustained tension of the sympathetic nervous system, and increased complaints of hypertension.[95]

In the case of physiological effects of noise on people living near commercial jet airports, a few studies have been conducted which indicate a direct relationship between high aircraft noise levels and increased physiological reactions. People living in areas where maximum A-weighted aircraft noise levels exceeded 100 dB complained to a significantly greater degree about problems related to nervousness, and digestive and cardiovascular systems than did people living in areas where aircraft noise levels were in the 80 to 90 dB range.[96] On a more objective basis, measurements of specific physiological responses in airport area residents subjected to various levels of aircraft noise indicated that reactions increased directly in proportion to noise level increase.[97] The change in specific physiological responses were related to the noise levels of the noise events, while the combined or "whole" reactions (physiological and psychological) were related to noise scales which combine noise level and number of events. There appeared to be no adaptation to aircraft noise. The study indicates that cardiovascular effects (increased blood pressure, etc.) result from the annoyance reactions to the aircraft noise exposure. The conclusions were that assessment of airport noise impact should be conducted using a cumulative type noise exposure rating scale (which combines event noise levels and number of events), and that realistic protection of the airport area residents' health requires a limit on maximum noise levels for single-events.

3.2.5 Behavioral and Performance Effects

3.2.5.1 Behavioral Effects

It has been suggested that specific and non-specific effects* of long-term exposure to intrusive/annoying noise can contribute to a chronic stress syndrome which is manifested by psychiatric disorders. A review of the literature discussing these cause-effect relationships indicates, for example, that every third person suffering neurosis and every fifth person with other mental disorders developed illness as a result of exposure to noise.[98]

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*Specific effects include auditory and behavorial responses, while other temporary and persisting physiological and psychological responses might be

Direct links between the higher exposure levels of aircraft noise and mental disorders in residents livig near airports have been difficult to establish conclusively. Studies near Heathrow Airport (London, England) and Los Angeles International Airport (California) have indicated a higher rate of admissions at psychiatric clinics for people living in the established aircraft noise zones.[99,100] The major criticism of these studies has been that demographic factors, rather than aircraft noise by itself, may be the cause of differences in the incidence of mental illnesses. However, preliminary results of a much larger and more recent study of residents near Heathrow airport once again are showing a higher rate of psychiatric admissions from high noise zones.[100] Analyses of other factors in the problem of showing cause and effect result in suggestions that in high noise areas where the people see no mechanism for combating the noise and despair of any alleviation, a greater rate of psychiatric problems will precipitate.

What is evident is that (obviously, it would seem) in areas of high noise exposure there is a marked increase in the proportion of people intensely annoyed. As there are more very annoyed people in the high noise zones, in numerical terms there will be more people suffering symptoms of ill-effects who are likely to attribute these symptons to the noise exposure. In regard to annnoyance related or aggravated psychological problems and demographic or other environmental factors, the criterion of rate of psychiatric admissions may not be sufficiently sensitive to always detect the acute or chronic effects of noise on people at risk in a large study population.

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*termed non-specific.[91] The non-specific responses include cardiovascular and other systematic changes such as blood pressure increase, muscular contractions, and heart rate increase. The persisting responses that have been indicated include chronic stress syndrome, psychosomatic disorders, and behaviorial and performance disorders.

3.2.5.2 Performance Effects

Many of the studies, and reviews of studies, regarding the effects of noise on human performance appear to be structured toward mental or physical tasks likely to occur in an occupational or military function. Moreover, these studies tend to examine the immediate or concurrent effects of noise on performance, rather than the effects on performance over a period of time, on people who are exposed to noise prior to and during the tasks. In fact, in a 1973 study to develop performance tests for assessment of noise stress effects, it was suggested that certain noise stresses may have their maximum effects on some tests after a brief exposure and on other tests only after extended exposure and performance durations.[101] Thus, it is not clear that such studies produce results that are relevant to the residential environment with high noise levels, or to the effects of noisy environments on the performance of children in school.

One such recent review of the effects of general noise on human performance was conducted for the purpose of predicting the effects of time-varying aircraft noise.[102] The predictions were that under certain conditions where only low or limited performance was necessary, aircraft noise would have no effect or an enhancing effect. In cases where performance at capacity was required, highly variable aircraft noise (irrelevant to the task performance) would result in performance decrements. However, the subject study did not include in its review many of the relevant studies available. For example, in one study it was found that the periodic presence of jet aircraft noise (at a perceived noise level of 100 dB) had no significant effect on the time-on-track of a paced visual tracking task.[103] The relevance of this study is not clear since most people around airports are probably not involved in specialized tasks similar to paced visual tracking. In another, perhaps more relevant study, it was found that both speed and accuracy on a memory-decision response task were degraded by test noises, including aircraft noise, at overall sound pressure levels in the 100 dB range.[104] Other studies have indicated that jet aircraft noise levels in the 90 dB (A-weighted) range contribute to an increase in mental fatigue and to inhibition of apptitude for performing tasks.[95] The results of performance tests in a more recent study examined indicated that A-weighted noise levels below 85 dB are not debilitative on some psychological tasks (reading), although it was reported that previous research had shown decrements in reading performance with higher (115 dB) noise levels.[105] Additionally, it was reported that moderate noise levels (84 dB) appear to act as a stressor for more sensitive people performing a difficult psychomotor task.

3.3 Assessment of the Applicability of Existing Health and Welfare Criteria to General Aviation Aircraft Noise and to General Aviation Airport Communities

There is little doubt that environmental noise contributes significantly to the general feeling of annoyance experienced by individuals living in the vicinity of major noise sources. Noise interferes with speech communications and disturbs sleep. Repeated exposure to noise of sufficient intensity for long periods of time will result in some degree of permanent loss of hearing. Other effects of noise on people include nonauditory physiological and behavioral reactions, and in some cases, noise may degrade physical and mental task performance. With respect to GA aircraft noise, relatively few studies have investigated the dose-response relationships associated with the above health and welfare noise effects categories, or the potential noise impact upon surrounding airport communities. Therefore, assessment of the applicability of existing health and welfare criteria to GA aircraft noise and to GA airport communities must be, for the most part, inferred from data and conclusions derived from studies involving commercial aircraft and other non-aircraft noise sources.

3.3.1 Individual Response

A review of earlier and more recent psychoacoustic research investigations concerning individual response to GA and commercial aircraft noise, as well as other noise sources, has identified some conflicting results regarding the choice of the optimum measure(s) for quantifying human response. The disagreement reported among the various studies reviewed is believed to be attributable to a number of experimental factors (see Section 3.1.1.4). However, based on available psychoacoustic test data specifically related to individual response to GA aircraft noise,[13,25] "rank-ordering" analyses were performed to evaluate the relative accuracy and consistency of a number of currently used frequency-weighted and calculated sound level measures. The following conclusions regarding the applicability of these currently used single-event measures to GA aircraft (small propeller-driven aircraft and helicopters) noise are:

1. The frequency-weighted sound level measures (L_A, L_B and L_D) are, on the average, more accurate than the calculated sound level measures (LL_S, LL_Z and L_{PN}). Also, for all practical purposes, the L_A, L_B and L_D are essentially indistinguishable. In terms of consistency, there is little difference between the frequency-weighted sound levels (L_A, L_B and L_D) and the calculated sound level measures (LL_S, LL_Z and L_{PN}).
2. Tone corrected perceived noise level is, on the average, less accurate than perceived noise level without a tone correction. With respect to consistency, there is little difference between the two perceived noise level measures.
3. The accuracy of the frequency-weighted sound level measures is, on the average, reduced by a duration allowance. The accuracy of the calculated sound level measures is, on the average, increased by a duration allowance. For both sound level measures, the consistency is, on the average, only marginally increased by a duration allowance.
4. The calculated sound level measures (LL_S, LL_Z and L_{PN}) with a duration allowance are, on the average, only marginally more accurate and more consistent than the frequency-weighted sound level measures (L_A, L_B and L_D) with a duration allowance.
5. The frequency-weighted sound level measures (L_A, L_B, and L_D) without a duration allowance and, the calculated sound level measures (LL_S, LL_Z and L_{PN}) with a duration allowance are, on the average, the most accurate and the most consistent currently used single-event measures. However, there are only marginal differences between these two sets of sound level measures.

Table 3-6 presents a summary listing the data used as the basis for above conclusions. Findings reported in other investigations specifically addressing individual response to GA aircraft noise tend to support the above conclusions.[39,41,42,44]

On the basis of providing reasonable accuracy and consistency in predicting subjective response, several of the currently used frequency-weighted sound level measures and calculated sound level measures are considered applicable to GA aircraft noise. For GA aircraft noise it

Table 3-6 Analysis of the Relative Accuracy and Consistency of Various Single-Event Measures Used to Predict Subjective Response to General Aviation Aircraft Noise. Derived from Data Presented on Tables 3-3 and 3-4.

	Frequency-Weighted Sound Level Measures						Calculated Sound Level Measures							
	Without Duration Allowance			With Duration Allowance			Without Duration Allowance				With Duration Allowance			
	L_A	L_B	L_D	$(L_A)_D$	$(L_B)_D$	$(L_D)_D$	LL_S	LL_Z	L_{PN}	$(L_{PN})_T$	$(LL_S)_D$	$(LL_Z)_D$	$(L_{PN})_D$	$(L_{PN})_{TD}$
Accuracy, dB	2.9	2.5	2.8	8.4	3.7	2.8	7.7	9.5	9.6	13.0	2.6	4.7	4.1	7.1
Consistency, dB	3.9	4.0	3.6	3.3	3.2	3.3	3.7	3.2	3.8	4.1	2.8	2.6	3.0	3.3

Legend:

L_A, L_B, L_D = frequency weighted sound levels
$(L_A)_D, (L_B)_D, (L_D)_D$ = frequency weighted sound levels with a duration allowance
L_{PN} = perceived noise level
$(L_{PN})_T$ = perceived noise level with tone correction
$(L_{PN})_{TD}$ = perceived noise level with tone correction and duration allowance
LL_S = Stevens's MK VI loudness calculation procedure
LL_Z = Zwicker's loudness calculation procedure
$(LL_S)_D$ = Stevens's MK VI loudness calculation procedure with duration allowance
$(LL_Z)_D$ = Zwicker's loudness calculation procedure with duration allowance

appears that a tone correction is not reqired, at least for the perceived noise level measures, and that a duration correction is beneficial only when applied to the calculated sound level measures. Therefore, with respect to GA aircraft noise, the selection of one of the currently used single-event measures over another will require a judgement regarding a trade-off between the degree of acceptable accuracy and consistency and the complexity associated with computing the value of the single-event measure.

3.3.2 Community Response

With respect to GA aircraft noise and GA airport operations, relatively little effort has been focused on quantifying community response to noise exposure. Most of the existing measures of community response to aircrfaft noise are based on the concept that the degree of annoyance experienced by individuals, and the community as a whole, can be adequately predicted by acoustical-energy summation models. The underlying assumption of these acoustical-energy models is that noise exposed populations will experience similar degrees of annoyance when exposed to equivalent levels of acoustical energy.

Although a number of investigations have presented study findings which question the general validity of the "equivalent-energy" concept,[50,56,57,58,59] there appears to be general agreement that: 1) the degree of annoyance experienced by populations exposed to aircraft noise is influenced by both the total number of noise events and the noise level amplitude of these events; and 2) prediction of community response to noise exposure based on a measure of the percent of the exposed population which is "highly annoyed" provides a more meaningful and useful means of assessing noise impact than other measures based on average or median response.

With only a few exceptions, most of the existing multiple-event measures used to quantify community noise exposure sum N noise events in accordance with the relationship, $K \log_{10} N$ where $K = 10$. Also, most of these measures include a weighting factor to account for varying noise sensitivity of people with time of day. Generally, nighttime noise exposure or noise levels are weighted by an additional 10 dB. Recent investigations have presented findings which tend to support the use of K = 10 as an appropriate value in the noise event summing relationship.[16,55] However, other recent investigations have reported findings which suggest that the 10 dB nighttime weighting is too high.[60,61,62,63,64] Notwithstanding these recent findings concerning the 10 dB nighttime weighting, results from a number of earlier and more recent social surveys[52,67,69] concerning noise from aircraft, as well as other noise sources, have shown good correlation and consistency between the percent of highly annoyed persons and day-night sound level (L_{dn}),a multiple-event measure which sums N noise events using a 10 log N relationship and applies a 10 dB weighting to nighttime noise events.

Therefore, with respect to GA aircraft noise exposure, there is little reason to expect that community annoyance response criteria based on relationships between percent highly annoyed and noise exposure measures such as L_{dn} would not be applicable to GA airport communities. However, findings from a number of community annoyance response studies, some specifically related to GA aircraft noise impact, have suggested that compared with the average response of communities around larger commercial airports: 1) the percentage of the population experiencing high annoyance (at a given noise exposure level) may be lower for GA airports;[50,56,57,58,74] and, 2) the noise exposure limit considered to be acceptable by most of the airport community may be as much as 15 dB lower for GA airports.[72,73] It is believed that these differences between commercial and GA airport community response are, most likely, due to lower overall noise exposure produced by GA aircraft operations and lower background, or ambient, noise levels around GA airports. Therefore, existing annoyance dose-response relationships (i.e., percent highly annoyed as a function noise exposure level) may not be applicable to GA airport communities.

3.3.3 Communication Interference

The Articulation Index (AI), the Speech Interference Level (SIL) and the Preferred Speech Interference Level (PSIL) are among the most prominent rating schemes developed specifically for quantifying the speech interference effects of noise. However, due to the complexity of the calculation procedure, the AI is not considered to be a practical means of measuring the interference effects of GA aircraft noise. Also, the SIL and the PSIL are not considered applicable to GA aircraft noise since neither accurately measures the masking of speech by noise containing intense low frequency components (below 500 Hz). As may be seen from Figures 2-1 and 2-3, typical propeller-driven aircraft and helicopter noise spectra are dominated by low frequency tones, generally below 500 Hz.

A number of investigations have been performed to assess the speech interference effects of aircraft flyover noise.[20,21,77,78] However, the findings resulting from these investigations are not directly applicable to GA aircraft noise since commercial jet (turbojet and turbofan) aircraft and large propeller-driven aircraft were the only aircraft types evaluated. Nevertheless, it was reported that the relationships between acceptability rating of aircraft noise and various single-event measures of the peak noise levels are essentially the same whether the rating was obtained in the absence of speech or with speech present at a comfortable listening level.[20,78] This finding suggests that dose-response measures relating acceptability and noise exposure might be equally as effective in estimating speech interference effects of GA aircraft noise.

The EPA "Levels Document"[52] presents speech communication criteria for outdoor and indoor noise environments in terms of percent sentence unintelligibility and A-weighted equivalent-continuous sound level. However, the EPA Airport/Aircraft Noise Study[70] pointed out that speech interference criteria based on average or equivalent-continuous sound level measures are best applied to environmental noises which are steady. It was also pointed out that the average or equivalent-continuous measures are conservative when applied to non-steady noises when the maximum levels do not cause a complete interruption of speech communication.

Hall et al.[74] conducted a social survey around an airport serving predominantly GA aircraft to investigate community response to noise from GA airport operations. It was reported that compared with the average response of communities around a large commercial airport, lower percentages of speech interference were reported by the GA airport community. However, this finding is, most likely, related more to differences between the amplitudes of GA aircraft noise as compared with commercial aircraft noise (see Table 2-2).

Based on the above findings, it is believed that existing communication criteria are not applicable to GA aircraft noise or to GA airport communities, and that annoyance (or acceptability) criteria are probably more applicable in assessing the impact of communication interference caused by GA aircraft noise than speech or communication criteria given in terms of percent of sentence unintelligibility.

3.3.4 Noise-Induced Hearing Loss

Only a few investigations have attempted to relate aircraft noise exposure and noise-induced hearing.[70,80,81,82] However, the criteria derived from these investigations are considered applicable to GA aircraft noise and to GA airport communities.

3.3.5 Sleep Disturbance

Several investigations have been performed to assess the effects of aircraft noise on sleep.[60,84,85,86] However, none of these investigations have produced quantitative dose-response relationships in terms of sleep disturbance and noise exposure level.

Lukas,[83,87] Thiessen[88] and Griefahn and Muzet[89] have recently developed sleep distrubance relationships given in terms of sleep disruption and sleep awakening as a function of single-event noise exposure level. The relationships developed by Lukas[83,87] were based on human response data related to a variety of noise sources, most of which (76 percent) were sub-sonic and supersonic jet aircraft. The relationships developed by Thiessen[88] were based on responses from a recording of a passing truck. The relationships developed by Griefahn and Muzet[89] were also based on responses related to various noise sources; however, the relative percentage of aircraft noise sources was not reported.

A comparison of the sleep disruption and sleep awakening criteria developed by Lukas[83,87] and Thiessen[88] show reasonably good agreement even though the noise stimuli were, for the most part, quite different. A comparison of the sleep disruption and sleep awakening criteria developed by Griefahn and Muzet[89] however, shows rather poor agreement with both the Lukas[83,87] and the Thiessen[88] criteria (see Figure 3-16 and 3-17 in Section 3.2.3).

Examination of the time history and octave band spectrum of the truck noise used by Thiessen[88] (Figure 2 in Reference 88) and time histories and noise spectra of several propeller-driven aircraft[106] shows remarkable similarity between the two noise source types. Therefore, on the basis of this similarity, it is concluded that the sleep disturbance criteria developed by Lukas[83,87] (and supported by criteria developed by Thiessen[88] are applicable to GA aircraft noise. However, it should be noted that, for the most part, the Griefahn and Muzet[89] criteria show less sleep disturbance sensitivity to noise as compared with the criteria developed by Lukas[83,87] and Thiessen.[88]

With respect to GA airport communities, the applicability of the existing sleep disturbance criteria is equivocal. Based on laboratory investigations, it has been reported that noise occurring randomly or infrequently (a situation which might be expected at GA airports with nighttime operations) is more disturbing than the same noise occurring regularly.[83,87,89] Additionally, based on findings from an investigation of community response to noise from GA aircraft operations, it was reported that compared with the average response of a community around a large commercial airport, a higher percentage of sleep disturbance was reported by the GA airport community.[74] It was suggested that the higher percentage of sleep disturbance reported by the GA airport community was probably due to greater noise sensitivity resulting from the infrequent nature of night flights. Lukas[83,87] reports that findings from one investigation have shown that sleep disturbance from low-density street traffic (1.8 vehicles/min.) was greater than that from high-density traffic (4.3 vehicles/min.), but the opposite result was obtained with jet aircraft noises.

3.3.6 Nonauditory Physiological and Behavioral Disorders and Task Performance Effects

Although growing evidence suggests a link between noise and a number of nonauditory physiological and behavioral disorders, and degradation of physical and mental task performance, definitive criteria for these noise effects categories have not yet been thoroughly quantified. Therefore, an assessment of the applicability of existing criteria for these noise effects categories to GA aircraft noise or to GA airport communities cannot be made at this time.

3.4 Conclusions and Recommendations

Based on an evaluation of existing health and welfare criteria and, an assessment of the applicability of these criteria to GA aircraft noise and to GA airport communities, the following conclusions and recommendations are presented:

Individual Response

On the basis of providing reasonable accuracy and consistency in predicting individual subjective response, several of the currently used frequency-weighted sound level measures and calculated sound level measures are considered applicable to GA aircraft noise. The frequency-weighted sound level measures (L_A, L_B and L_D) without a duration allowance (or correction) and the calculated sound level measures (LL_S, LL_Z and L_{PN}) with a duration allowance are, on the average, the most accurate and the most consistent currently used single-event measurea of GA aircraft noise. However, there are only marginal differences between these two sets of sound level measures. Therefore, it is recommended that the simpler frequency-weighted sound measures (L_A,L_B and L_D), without a duration correction, be used to assess individual subjective response to GA aircraft noise. Since, for all practical purposes, the L_A, L_B and L_D are essentially indistinguishable, all three of these frequency-weighted sound level measures are considered equivalent with respect to predicting individual subjective response.

Community Response

There is little reason to expect that community annoyance response criteria based on a relationship between percent highly annoyed and noise exposure measures such as day-night sound level would not be applicable to GA airport communities. However, findings from a number of community annoyance response studies suggest that existing community annoyance criteria may not be applicable to GA airport communities. Therefore, the following recommendations are presented:

1. Community noise surveys should be conducted around several representative GA airports to obtain additional data relating annoyance response to GA aircraft noise exposure.
2. Based on the results of the GA airport community noise survey, annoyance criteria should be developed and compared with existing community annoyance criteria to determine their degree of correlation.
3. Until annoyance criteria are developed specifically for GA airport communities, the dose-response relationship developed by Schultz[67] should be used to assess community annoyance from GA aircraft noise exposure.

Communication Interference

Existing communication criteria are not, for the most part, applicable to GA aircraft noise or to GA airport communities. However, because of the time-varying nature of aircraft noise exposure, it is believed that annoyance (or acceptability) criteria are probably more applicable in assessing the impact of communication interference caused by GA aircraft noise than speech or communication criteria given in terms of percent of sentence unintelligibility.

Noise-Induced Hearing Loss

Existing noise-induced hearing loss criteria are considered applicable to GA aircraft noise and to GA airport communities. Although it is believed that the criteria identified in the EPA "Levels Document"[52] overestimate the effects of GA aircraft noise exposure, it is recommended these criteria be used to assess the potential noise-induced hearing loss impact upon GA airport community residents.

Sleep Disturbance

Existing sleep disturbance criteria are considered applicable to GA aircraft noise. However, with respect to GA airport communities, the applicability of the existing sleep disturbance criteria is equivocal. Findings from a number of studies suggest that random or infrequent occurrences of noise (a situation which might be expected at GA airports with nighttime operations) are more disturbing than the same noise occurring regularly. Therefore, it is recommended that laboratory and field studies be conducted to obtain response data specifically addressing the relative sleep disturbance effects of random or infrequent noise occurrences as compared with regular or uniform noise occurrences. Also, until these data are available, it is recommended that criteria developed by Lukas[83,87] (and supported by criteria developed by Thiessen[88]) be used to assess the sleep disturbance effects of GA aircraft noise upon GA airport communities residents.

Nonauditory Physiological and Behavioral Disorders and Task Performance Effects

Although growing evidence suggests a link between noise and a number of nonauditory physiological and behavioral disorders, and degradation of physical and mental task performance, definitive criteria for these noise effects categories have not yet been thoroughly quantified. Therefore, an assessment of the applicability of existing criteria for these noise effects categories to GA aircraft noise and to GA airport communities cannot be made at this time.

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APPENDIX A

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APPENDIX B

GENERAL AVIATION (GA) AIRCRAFT/AIRPORT PARAMETERS WHICH INFLUENCE THE EXTENT OF COMMUNITY NOISE IMPACT

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GENERAL AVIATION (GA) AIRCRAFT/AIRPORT PARAMETERS WHICH INFLUENCE THE EXTENT OF COMMUNITY NOISE IMPACT

This Appendix presents data related to some of the key physical parameters which influence the noise impact on communities surrounding GA airports. Since there is no recognized definition of GA airports, it has been necessary to define these airports as th ose which serve predominantly GA type aircraft. A definition of GA airports, in quantitative terms, has been developed from data presented in Federal Aviation Administration (FAA) publications and is discussed in Section B.2.

In addition to the noise emission characteristics and overall noise levels associated with GA aircraft, a number of other physical parameters have been identified which have significant influence on the assessment on community noise impact resulting from aircraft operations. These parameters are:

1. Mix of aircraft types
2. Level and distribution of daily operations (by airport type)
3. Flight procedures
4. Population distribution (or density) around airports

In the following sections, data concerning each of these physical parameters will be discussed. A baseline calendar year (CY) of 1975 has been selected. The choice of 1975 as a reference year was based on a number of considerations: 1) baseline year of CY 1975 is consistent with other EPA contract efforts involving GA noise impact; 2) due to the inherent time lag associated with the assimilation and the distribution of aircraft activity data, CY 1975 represents the most complete collection of relevant statistical data currently available; and 3) a significant body of activity data concerning the level and distribution of GA aircraft operations at GA airports has been collected and evaluated by the Office Management Systems of the FAA in CY 1975.

body of activity data concerning the level and distribution of GA aircraft operations at GA airports has been collected and evaluated by the Office Management Systems of the FAA in CY 1975.

B.1 MIX OF GA AIRCRAFT TYPES

Relevant statistical data concerning the mix of GA aircraft are generally given in terms of aircraft type and primary use categories. Two sources were found which identified the mix of GA aircraft by type and by primary use category: 1) FAA Statistical Handbook of Aviation[1], and 2) Selected Statistics, United States General Aviation 1959-1975[2]. Based on data presented in these two documents, values of the average GA aircraft fleet size and mix were determined in accordance with the following aircraft types and primary use categories:

Aircraft Type

- Single Engine Piston, 1-3 seats
- Single Engine Piston, 4 or more seats
- Twin Engine Piston, Less than 12,500 lbs.
- Multi-Engine Piston, Greater than 12, 500 lbs.
- Turboprop
- Turbojet
- Turbofan
- Helicopter-Piston
- Helicopter-Turbine

Primary Use Category

- Executive
- Business
- Personal
- Aerial Applications
- Instructional
- Air Taxi
- Industrial/special
- Rental
- Other

An estimated distribution of the mix of active (CY 75) GA aircraft by type and primary use category is shown in Table B-1. The data shown in Table B-1 does not reflect the actual relative mix or level of daily operations occurring at GA airports. However, based on data obtained from a 1975 GA activity survey conducted at 245 public use

Table B-1. ESTIMATED DISTRIBUTION OF ACTIVE (CY 75) GA AIRCRAFT BY TYPE AND BY PRIMARY USE

Aircraft Type	Primary Use of Aircraft									Total
	Executive	Business	Personal	Aerial Application	Instructional	Air Taxi	Industrial/ Special	Rental	Other	
Single Engine Piston 1-3 Seats	165	3069	29835	6216	6458	119	638	2448	1593	50541 (30.6)
Single Engine Piston 4 or more Seats	1416	26438	45460	164	5129	1854	809	4347	1200	86817 (52.5)
Twin Engine Piston <12,500 lbs.	4163	7548	2049	100	615	2660	234	398	459	19122 (11.6)
Multi-Engine Piston ≥12,500 lbs.	205	372	120	126	26	150	36	48	71	1154 (0.7)
Turboprop	1467	231	43	3	0	334	18	18	74	2196 (1.3)
Turbojet	957	45	13	5	0	96	4	12	77	1217 (0.7)
Turbofan*	319	15	5	1	2	32	2	4	26	406 (0.2)
Helicopter-Piston	144	294	195	552	215	272	644	29	165	2510 (1.5)
Helicoper-Turbine	321	84	33	27	0	566	129	6	131	1305 (0.8)
Total	9157 (5.5)	38096 (23.1)	78553 (47.5)	7282 (4.4)	12469 (7.5)	6091 (3.7)	2514 (1.5)	7310 (4.4)	3796 (2.3)	165,260 (100)**

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*It is assumed that turbofan aircraft represent approximately 25% of total GA jet fleet.

**Totals may not sum to 100 percent due to rounding

Note: Numbers in parentheses represent percent of total GA aircraft fleet.

Source: References 1 and 2.

airports in all 50 United States by the Office of Management Systems[3] of the FAA, a comparison of the estimated active GA fleet distributuion with actual daily GA operations by aircraft type and primary use can be made. These comparisons are shown in Tables B-2 and B-3. It can be seen that, based on available data, the distribution of the GA fleet mix, in terms of percent of total fleet size, is representative of the actual distribution of daily GA aircraft activity.

B.2 LEVEL AND DISTRIBUTION OF GA AIRCRAFT OPERATIONS BY AIRPORT TYPE

FAA statistical data show that in 1975, there were approximately 60 million aircraft operations at FAA-towered U. S. civil and joint-use land facilities.[1] Of this total,approximately 45 million operations were performed by GA type aircraft. It was estimated that GA operations at the over 400 FAA-towered airports represented only about 34 percent of the total number of GA operations in CY 1975.[3] The remaining 66 percent, or approximately 86 million operations occurred at non-FAA towered and non-towered public and private use airports. Additionally, it was estimated that about 7,000 or 53 percent of the more than 13,000 landing facilities on record with the FAA were open to public use and handled at least 95 percent of all GA aircraft operations. Non-towered public use airports can be categorized according to the type(s) of runway surface(s) and the lighting system(s) in operation. Table B-4 presents a summary listing of the estimated distribution of U. S. civil and joint-use airports on record with the FAA in CY 1975.

Aircraft activity data concerning level and distribution of operations at a given airport are recorded or estimated in terms of general aircraft categories and operations, i.e., all aircraft are categorized as GA, air taxi (AT), commercial air carrier (AC), or military types, and operations are counted as either local or itinerant.* Only FAA-towered airports

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*Local operations are typically training flights consisting of touch-and-goes or short distance or duration operations. Itinerant operations are defined as an arrival operation at an airport by an aircraft which has not departed that airport in the previous 30 minutes or a departure from an airport by an aircraft which does not return to that airport in the following 30 minutes.

Table B-2. DISTRIBUTION OF ACTIVE GA AIRCRAFT FLEET BY AIRCRAFT TYPE; CY 1975

ACTIVE GENERAL AVIATION AIRCRAFT FLEET BY AIRCRAFT TYPE (CY 75)

Aircraft Type	1/ No.	1/ %	2/ No.	2/ %	3/ No.	3/ %
Single-engine Piston; 1-3 Places	51378	31.0	49699	30.2	1910	27.2
Single-engine Piston; 4 Places and over	86117	51.9	87514	53.2	3684	52.4
Multi-engine Piston	20330	12.2	20213	12.3	951	13.5
Turboprop	2519	1.5	1869	1.1	216	3.1
Turbojet	1331	0.8	1098	0.7	119(*)	1.7
Turbofan	444	0.3	366	0.2	39(*)	0.6
Helicopter-Piston	2279	1.4	2737	1.7	75(**)	1.0
Helicopter-Turbine	1563	0.9	1042	0.6	38(**)	0.5
TOTALS	165,961	100.0	164,538	100.0	7,032	100.0

1/ - FAA STAT. HANDBROOK - CY 1975 (Ref. 1)

2/ - FAA-AVP-76-12-CY 1975 (Ref. 2)

3/ - 1975 GA ACTIVITY SURVEY (Ref. 3)

* - Based on the assumption that turbojet and turbogan aircraft represent approximately 75% and 25%, respectively, of the total GA jet fleet.

** - Based on the average distribution of Piston and Turbine types as presented in 1/ and 2/.

Table B-3. DISTRIBUTION OF ACTIVE GA AIRCRAFT FLEET BY AIRCRAFT USE; CY 1975

ACTIVE GENERAL AVIATION AIRCRAFT FLEET BY AIRCRAFT USE (CY 75)						
	1/		2/		3/	
Aircraft Type	No.	%	No.	%	No.	%
Executive	9342	5.6	8970	5.5	432	6.2
Business	35415	21.3	40773	24.8	1409	20.1
Personal	81084	48.9	76015	46.2	3057	43.6
Aerial Application	7176	4.3	7383	4.5	70	1.0
Instructional	12419	7.5	12514	7.6	1387	19.8
Air Taxi(*)	6331	3.8	5848	3.6	330	4.7
Industrial/Special	2544	1.5	2479	1.5	91	1.3
Rental	7689	4.6	6929	4.2	***	-
Other(**)	3961	2.4	3627	2.2	236	3.4
TOTAL	165,961	100.0	164,538	100.0	7012	100.0

1/ - FAA STAT. HANDBROOK - CY 1975 (Ref. 1)

2/ - FAA-AVP-76-12-CY 1975 (Ref. 2)

3/ - 1975 GA ACTIVITY SURVEY (Ref. 3)

* - Includes Commuter Air Carrier

** - Glider Activity Subtracted from this Category

*** - Included in other use Categories

Table B-4. ESTIMATED DISTRIBUTION OF U.S. CIVIL AND JOINT-USE AIRPORTS ON RECORD WITH FAA IN CALENDAR YEAR 1975.*

AIRPORT CLASSIFICATION	AIRPORTS OPEN TO PUBLIC	AIRPORTS NOT OPEN TO PUBLIC	TOTAL
TOTAL TOWERED AIRPORTS			
FAA	407		407
NON-FAA	40	4	44
TOTAL NONTOWERED AIRPORTS			
PAVED AND LIGHTED	2,568	203	2,771
PAVED AND UNLIGHTED	519	801	1,320
UNPAVED AND LIGHTED	535	173	708
UNPAVED AND UNLIGHTED	1,940	4,002	5,942
TOTAL	6,009	5,183	11,192

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* Excludes heliports, stolports, and seaplane bases.

maintain daily records of aircraft operational data. These data are recorded on standard FAA forms and are used as the basis for a number of FAA statistical publications. The non-towered public use airports provide only estimates of the number of annual local and itinerant aircraft operations. Neither the towered or non-towered airports provide operational counts by specific aircraft type or type of operation. Therefore, the published FAA statistical data concerning aircraft activity at various types of public use airports is not sufficient to provide a detailed distribution of the level of operations performed by specific aircraft types. However, in 1975, the Office of Management Systems of the FAA conducted an extensive GA activity survey at 245 airports in all 50 United States. Of the 245 airports surveyed, 63 had FAA towers, eight had non-FAA operated towers and 174 had no tower. The 174 non-towered airports included those with runway(s) which were: 1) paved and lighted 2) paved and unlighted 3) unpaved and lighted, and 4) unpaved and unlighted. Operational data were recorded in terms of the number and type of operation performed by specific GA aircraft types at each airport surveyed. A computer tape file containing a complete listing of all of the survey data was obtained and installed on the EPA's computer system. Based on published FAA statistical data,[4,5,6] the airports included in the 1975 activity survey were arranged according to the actual or estimated total number of annual operations for CY 1975. These airports were then grouped according to tower status (towered or non-towered) and according to airport type, i.e., GA or commercial air carrier (AC). An airport was classified as a GA airport if it was:

1. Towered and the ratio of total annual GA (plus air taxi) operations to total annual operations is equal to or greater than 0.85; all other towered airports are classified commercial air carriers; (see footnote*).

2. Non-towered

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*Criteria for the towered airport classifications are based on statistical data concerning level of operations at airports specified as General Aviation Airports in "FAA Air Traffic Activity, CY 1975" (Ref. 5).

All airport types, towered or non-towered were arranged according to the level of total annual operations. Additionally, non-towered airports were grouped according to the configuration of the runway(s) (i.e., paved or unpaved and lighted or unlighted). Table B-5 presents a summary listing of the airport categorization scheme used in evaluating the level and distribution of GA aircraft operations at each airport type. Table B-5 was developed from statistical data presented in FAA publications.[4,5,6]

Table B-6 presents a listing of the level and distribution of GA aircraft operations for each airport type identified in Table B-5. These data are based on the results of the 1975 GA activity survey performed by the FAA and are given in terms of the percent of total operations recorded at each airport, for each aircraft type. Because the survey data were collected for two separate days, one weekday and one weekend day, the average percent of total operations has been adjusted to account for the probable differences between the average level of weekday and weekend day operations. This adjustment was made using the following equation:

$$\text{Adj\%} = \frac{1}{7}\left[(5 \times \text{WD\%}) + (2 \times \text{WED\%})\right]$$

where Adj% = adjusted average weekly percentage of aircraft operations,
WD% = weekday percentage of aircraft operations,
WED% = weekend day percentage of aircraft operations.

B.3 FLIGHT PROCEDURES USED AT GA AIRPORTS

The flight procedures used on takeoff or landing can have significant effects on the degree of noise exposure produced in surrounding airport communities. Unlike the procedures used by larger commercial jet aircraft, GA flight procedures are not as well defined, particularly at non-towered airports. Although many towered, as well as non-towered airports, do have specific takeoff and landing operational procedures, there is little standardization among all airport types.

Table B-5. CLASSIFICATION OF TOWERED AND NON-TOWERED AIRPORTS USED IN EVALUATION OF LEVEL AND DISTRIBUTION OF CY 75 GA OPERATIONS*

Tower Status and Airport Type(s)	Volume Category	Range of Total Annual Aircraft Operations	Average Number of Total Annual Aircraft Operations	Number of Airports Considered	Ratio of Average GA** to Average Total Operations
Towered (GA plus AT)	LOW	Less than or equal to 100,000	65,000	69	0.91
	MEDIUM	101,000-200,000	154,000	84	0.94
	HIGH	Greater than 201,000	282,000	45	0.99
Towered (AC)	LOW	Less than or equal to 100,000	69,000	96	0.78
	MEDIUM	101,000-200,000	142,000	74	0.70
	HIGH	Greater than 201,000	289,000	42	0.52
Non-Towered, Paved Runways-Lighted and Unlighted	LOW	Less than or equal to 25,000	17,000	144	0.88
	MEDIUM	26,000-50,000	36,000	153	0.92
	HIGH	Greater than 51,000	88,000	104	0.93
Non-Towered, Unpaved Runways-Lighted and Unlighted	AVERAGE	2,000-47,000	18,000	20	0.90

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[*] Based on FAA statistical data presented in References 4, 5, and 6

[**] Includes general aviation plus air taxi.

Table B-6. LEVEL AND DISTRIBUTION OF DAILY GA AIRCRAFT OPERATINONS AS DETERMINED FROM CY 1975 GA ACTIVITY SURVEY (REF.3), VALUES GIVEN IN TERMS OF PERCENTAGE OF TOTAL OPERATIONS RECORDED

			Piston-Engined											
Tower Status and Airport Type(s)	Volume Category	Number of Airports Considered	Single-Engine, 1 - 3 Seats		Single-Engine, 4 or More Seats		Multi-Engine		Turboprop		Turbojet/Fan		Helicopter	
			I*	L**	I	L	I	L	I	L	I	L	I	L
Towered (GA plus AT)	LOW	10	29.94	7.27	37.72	6.88	9.89	0.30	4.26	0.12	1.89	0.18	1.49	0.06
	MEDIUM	12	28.43	5.75	42.60	6.43	9.17	0.41	2.79	0.07	1.63	0	2.69	0.09
	HIGH	2	19.11	1.13	64.46	1.88	8.79	0.0	1.88	0.0	0.50	0.75	1.51	0.0
Towered (AC)	LOW	9	23.51	5.21	35.34	14.44	10.22	4.20	1.95	2.02	2.07	0.42	0.49	0.11
	MEDIUM	15	26.0	1.46	42.61	0.66	16.45	0.06	4.63	0.0	6.23	0.10	1.78	0.0
	HIGH	6	22.39	5.56	39.55	9.24	13.69	0.75	2.63	0.0	5.32	0.34	0.53	0.0
Non-Towered, Paved Runways - Lighted and Unlighted	LOW	8	36.98	12.14	26.23	9.82	6.03	1.22	2.53	0.0	0.28	0.0	4.16	0.62
	MEDIUM	13	36.81	3.11	44.70	1.60	9.55	0.11	1.69	0.0	0.97	0.08	1.38	0.0
	HIGH	8	30.67	2.64	55.81	4.20	4.90	0.14	0.76	0.0	0.11	0.0	0.69	0.07
Non-Towered, Unpaved Runways - Lighted and Unlighted	AVERAGE	17	41.81	8.97	35.13	7.97	4.47	0.0	0.0	0.0	0.0	0.0	1.65	0.0

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* I - Itinerant operations defined as takeoffs or landings.

** L - Local operations defined as "touch-and-goes" (counted as two operations).

Note: Rows may not sum to 100 percent due to rounding.

Flight procedures vary from airport to airport for several reasons including: 1) operational restrictions imposed by the airport operator or the FAA, 2) types and dimensions of available runways, 3) geographical features surrounding the airport, and 4) variability in piloting techniques. Additionally, flight procedures used at a given airport vary due to weather conditions, pilot experience, traffic volume, and types of aircraft using the airport.

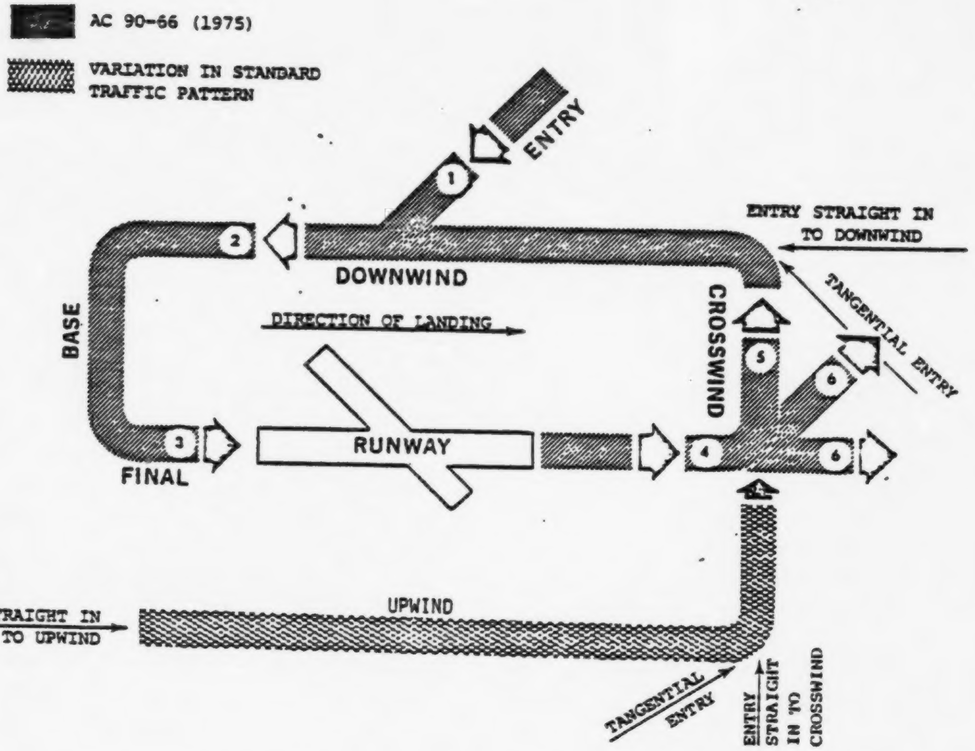
B.3.1 Landing Procedures

Landings are generally accomplished from a traffic pattern used to insure an orderly flow of traffic into the airport. Traffic patterns are typically designated as either "left" or "right" patterns which consist of separate flight paths or "legs" around a runway of the airport. These legs are termed:

1. Upwind leg
2. Crosswind leg
3. Downwind leg
4. Base leg
5. Final leg

The traffic pattern is entered at a specified Traffic Pattern Altitude (TPA) typically 800 feet, but this varies from airport to airport. A number of studies[7,8,9,10] have shown that actual approach and landing procedures vary considerably from the structured left and right patterns recommended by a particular airport.

However, in an attempt to achieve some standardization in the flight procedures at non-towered airports, the FAA has recently published an Advisory Circular AC 90-66, "Recommended Standard Traffic Patterns for Airline Operations at Uncontrolled Airports". This advisory circular recommends that a downwind entry mid-point of the runway be used and that specific departure procedures be used to minimize conflict with traffic using the crosswind leg. The FAA recommended traffic patterns and descriptions are shown in Figures B-1 and B-2. Also shown in these figures are typically used upwind entries to the recommended traffic pattern.



AC 90-66 (1975)
VARIATION IN STANDARD TRAFFIC PATTERN
ENTRY
1
2
DOWNWIND
ENTRY STRAIGHT IN TO DOWNWIND
TANGENTIAL ENTRY
CROSSWIND
BASE
DIRECTION OF LANDING
5
6
3
RUNWAY
4
6
FINAL
ENTRY STRAIGHT IN TO UPWIND
UPWIND
TANGENTIAL ENTRY
ENTRY STRAIGHT IN TO CROSSWIND

RECOMMENDED STANDARD LEFT TRAFFIC PATTERN

1 Enter pattern in level flight, abeam the midpoint of the runway, at pattern altitude.

2 Maintain pattern altitude until abeam approach end of the landing runway, on downwind leg.

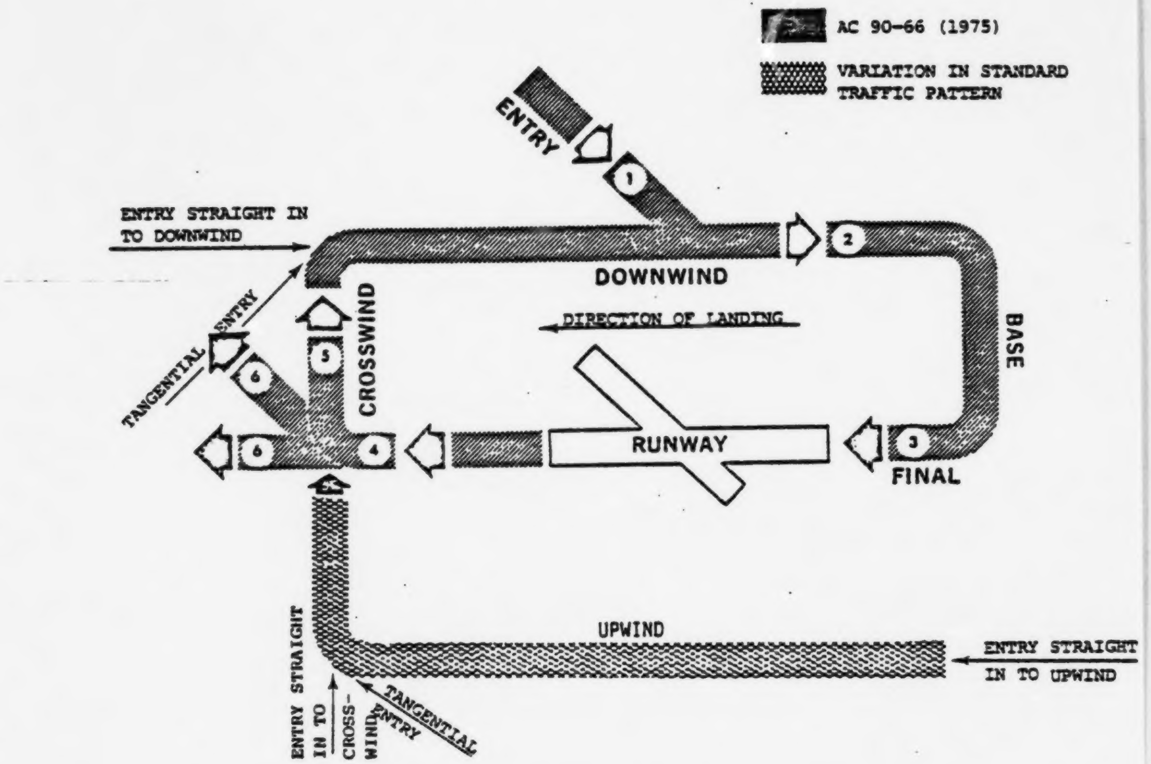
3 Complete turn to final at least 1/4 mile from runway.

4 Continue straight ahead until beyond departure end of runway.

5 If remaining in the traffic pattern, commence turn to crosswind leg beyond the departure end of the runway, within 300 feet of pattern altitude.

6 If departing the traffic pattern, continue straight out, or exit with a 45° left turn beyond the departure end of the runway, after reaching pattern altitude.

FIGURE B-1. ILLUSTRATION OF FAA AC 90-66 STANDARD LEFT TRAFFIC PATTERN (SLTP)


AC 90-66 (1975)
VARIATION IN STANDARD TRAFFIC PATTERN
ENTRY
1
2
3
4
5
6
6
ENTRY STRAIGHT IN TO DOWNWIND
DOWNWIND
DIRECTION OF LANDING
BASE
CROSSWIND
TANGENTIAL ENTRY
RUNWAY
FINAL
UPWIND
ENTRY STRAIGHT IN TO UPWIND
ENTRY STRAIGHT IN TO CROSS-WIND
TANGENTIAL ENTRY

RECOMMENDED STANDARD RIGHT TRAFFIC PATTERN

1 Enter pattern in level flight, abeam the midpoint of the runway, at pattern altitude.

2 Maintain pattern altitude until abeam approach end of the landing runway, on downwind leg.

3 Complete turn to final at least 1/4 mile from runway.

4 Continue straight ahead until beyond departure end of runway.

5 If remaining in the traffic pattern, commence turn to crosswind leg beyond the departure end of the runway, within 300 feet of pattern altitude.

6 If departing the traffic pattern, continue straight out, or exit with a 45° right turn beyond the departure end of the runway, upon reaching pattern altitude.

FIGURE B-2. ILLUSTRATION OF FAA AC-90-66 STANDARD RIGHT TRAFFIC PATTERN (SRTP)

B.3.2 Takeoff Procedures

Considerable effort has been focused on identifying the optimal noise abatement takeoff procedure(s) for the larger commercial jet aircraft. Relatively little attention however has been given to the small GA aircraft types. Because of considerable differences in performance characteristics between larger commercial aircraft and GA type aircraft, it is unclear whether flight procedures which have been demonstrated to provide noise level reductions for the commercial avaiation fleet are applicable to the GA aircraft fleet. Additionally, it is not clear whether a single takeoff flight procedure would be appropriate for all GA aircraft types. However, based on limited available information and on results from analyses involving larger commercial aircraft, it is unlikely that a single "best" procedure could be used by all GA aircraft types.

In general, GA aircraft takeoffs can be classified as either: 1) normal, 2) short field, or 3) obstacle. The normal takeoffs are typically made with zero degree flap retraction, normal takeoff power setting and aircraft pitch attitude to achieve "best rate of climb." The short field and obstacle takeoffs are usually made with flaps extended, maximum takeoff power (or at least greater than normal takeoff power), and aircraft pitch attitude to achieve "best angle of climb". These procedures are more related to safety considerations than noise abatement or control.

Recently, Aarons[11] examined a number of noise control takeoff procedures using three GA aircraft types: 1) a twin-engine jet, 2) a twin-engine piston (propeller), and 3) a single-engine piston (propeller). Three flight procedures were used for both piston engine aircraft and two for the jet. Aarons concluded that the flight procedure which was best, in terms of noise reduction _and_ safety, for one aircraft type was not best for the other aircraft types. It was concluded that the optimal takeoff flight procedure for each GA aircraft was:

- Twin-engine jet - Retract gear after a positive climb rate is established. This is followed by an immediate partial flap retraction from initial takeoff flaps and at the same time reduce power to a setting which is slightly higher than the FAA engine-out requirement (FAR-25).

- Twin-engine piston - Retract gear when insufficient runway remains for a straight ahead landing, and maintain maximum climb power. At 500 feet above ground level, reduce power to normal climb setting. (Note: no flap setting configurations were given).
- Single-engine piston - Climb at 70 knots (IAS) with takeoff power and zero flaps to 500 feet above ground level. At 500 feet, reduce power to recommended normal climb setting.

B.4 POPULATION DISTRIBUTION (DENSITY) AROUND GA AND NON-GA AIRPORTS

Average population densities around towered and non-towered GA and non-GA airports have been determined for a representative sample of airport types identified in Table B-5. These data were obtained from the Office of Environment and Energy of the FAA which provided a listing of the populations within a radius of from 2 to 10 miles, in two mile increments, around over 1500 towered and non-towered airports in the U. S. The population data are based on the 1970 U. S. Population Census. The population density values were determined from total population and total land area within circular areas from 2 to 10 miles, in two-mile increments, for each airport type. Except for the first two-mile radius distance, average population densities were determined for circular bands, in two-mile increments, out to 10 miles from each airport. For the first two-mile radius value, the average population densities were determined from the total population and total land area within the two-mile radius distance, minus the airport area. The average population density value within a 5-mile radius of each airport type was also determined. A sample of the FAA listings is shown in Figure B-3. Table B-7 presents a summary of the population densities determined from the complete listings provided by the FAA.

B.5 ESTIMATED NOISE IMPACT UPON GA AIRPORT COMMUNITIES RESULTING FROM GA AIRCRAFT OPERATIONS

The EPA "Levels Document"[12] has identified 55 dB as the outdoor yearly day-night sound level (L_{dn}) requisite to protect public health and welfare from the effects of environmental noise. People living in areas exposed to noise levels greater than L_{dn} of 55 dB will be expected to experience some degree of noise impact. Therefore, the estimated noise impact upon GA airport communities resulting from GA aircraft operations will be quantified in terms of the number of people exposed to L_{dn} values of 55 dB or greater.

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                    DAILY OPERATIONS AND POPULATION AT U.S. AIRPORTS
                                 FOR TOWERED AIRPORTS

                      (DATA FROM AEE AIRPORT INFORMATION FILE -AUG78-)

                                                                         POP     POP     POP     POP     POP
                                                          GA/TOT  ARPT   2MI     4MI     6MI     8MI     10MI
LOCID  CITY              STATE  GAOPS  MILOPS SCHEDOPS TOTOPS  RATIO  ACRES RADIUS  RADIUS  RADIUS  RADIUS  RADIUS   RANK

 LAX   LOS ANGELES        CA   1565.9   13.2  1311.0   2890.1  .54    3500  48493  250770  646592 1239829 1856259    1
 ORD   CHICAGO            IL    396.1   12.7  2060.2   2469.0  .16    7000   3564   98352  477726  892900 1473457    2
 SNA   SANTA ANA          CA   1757.3    2.1   140.2   1899.6  .92     492  17433  122931  335797  512163  724279    3
 VNY   VAN NUYS           CA   1675.7   10.1    10.0   1695.8  .98     725      0       0       0       0       0    4
 LGB   LONG BEACH         CA   1520.2    4.7    58.0   1582.9  .96    1314  55252  389812  656506 1067577 1582963    5
 ATL   ATLANTA            GA    154.2   16.7  1382.2   1553.1  .09    3800  18315   97467  220043  360643  574483    6
 DEN   DENVER             CO    538.0    3.5   975.0   1516.5  .35    4600  41306  164438  346243  512533  734505    7
 SJC   SAN JOSE           CA   1088.0    2.7   213.5   1304.2  .84    1050  41044  208136  494413  753070  901862    8
 MEM   MEMPHIS            TN    879.1   13.7   474.0   1366.8  .64    3056   6598  122538  271040  489209  607975    9
 BOS   BOSTON             MA    495.0    5.0   800.7   1300.7  .38    2384  51482  269814  725248 1247631 1634463   10
 DFW   DALLAS-FORT WOR    TX    178.3    1.4  1094.1   1273.8  .13   17520      0   22651   69242  114263  234641   11
 OPF   MIAMI              FL   1219.5   17.1      .0   1236.6  .98    1810  36240  153227  341487  599969  865073   12
 PHX   PHOENIX            AZ    883.6   32.9   306.0   1222.5  .72    1650  25094  155867  358409  474083  616457   13
 PHL   PHILADELPHIA       PA    494.0    5.6   699.0   1198.6  .41    2500   9822  141147  572146 1191494 1760872   14
 PIT   PITTSBURGH         PA    423.8   32.2   728.2   1184.2  .35   10000      0   29874   60382  119587  252675   15
 SFO   SAN FRANCISCO      CA    233.4   13.4   936.1   1182.9  .19    5207  18130  115944  204538  436402  643179   16
 BFI   SEATTLE            WA   1150.0    6.9     3.4   1160.3  .99     575  23329  149388  337940  466145  657788   17
 TOA   TORRANCE           CA   1129.7    1.7      .0   1131.4  .99     506  75113  250194  519052  750807 1132135   18
 OAK   OAKLAND            CA    944.0   14.9   152.8   1111.7  .84   13135   9463  181167  397893  577194  782507   19
 DAL   DALLAS             TX    841.3    5.8   227.8   1074.9  .78    1280  42986  126808  339602  581047  844001   20
 HWD   HAYWARD            CA   1069.8    4.6      .0   1074.4  .99     543  37883  204295  285132  356308  499231   21
 DCA   WASHINGTON         DC    365.2    1.3   694.5   1061.0  .34     861  52772  416509  936406 1357707 1752560   22
 PTK   PONTIAC            MI   1057.0     .8     2.8   1060.6  .99     438  22013   67434  136173  219850  282921   23
 HNL   HONOLULU           HI    481.3   97.5   460.0   1038.8  .46    4220  13859  105292  227861  351682  456791   24
 RHV   SAN JOSE           CA   1032.8     .5      .0   1033.3  .99     179  64727  174514  276439  476712  654460   25
 HOU   HOUSTON            TX    836.6    3.3   168.1   1008.0  .82    1304  23305  128930  280178  486674  644049   26
 CCR   CONCORD            CA    989.7    1.5    16.7   1007.9  .98     578  27172  113164  183365  240364  296463   27
 DTW   DETROIT            MI    474.3     .4   532.7   1007.4  .47    5000   7525   42733  190879  401427  696829   28
 STL   ST LOUIS           MO    376.8   31.3   594.4   1002.5  .37    2000  30362  209885  408706  681161  974142   29
 LGA   NEW YORK           NY    167.0    5.5   828.8   1001.3  .16     580 174109 1326496 3309441 5504602 6966849   30
 MRI   ANCHORAGE          AK    977.0     .0      .0    977.0  .00     248  36356   93360  103370  117039  120191   31
 MIA   MIAMI              FL    229.8    2.1   722.0    953.9  .24    2699  33006  239402  597717  765208  973022   32
 JFK   NEW YORK           NY    149.5    1.5   794.2    945.2  .15    5200  12054  392906  979253 2032959 3649725   33
 FLL   FT LAUDERDALE      FL    692.0    3.6   244.7    940.3  .73    1180  23349   98814  245805  425938  567332   34
 CMH   COLUMBUS           OH    720.6    7.7   178.8    907.1  .79    1800  27481  131649  311916  506150  677205   35
 TMB   MIAMI              FL    903.5    3.3      .0    906.8  .99    1292      0   11656   53908  157293  232069   36
 ISP   ISLIP              NY    814.8   26.2    32.8    873.8  .93    1350  35570   76220  187404  327940  479729   37
 LAS   LAS VEGAS          NV    518.3    9.9   338.5    866.7  .59    1678   4968   25433   95062  169233  228562   38
 TUS   TUCSON             AZ    635.6  109.6   110.8    856.0  .74    2200   8437   26398   70617  144562  232387   39
 SPS   WICHITA FALLS      TX    125.6  691.8    33.1    850.5  .14    3800  10703   16437   44000   76914  107154   40
 ROC   ROCHESTER          NY    720.8     .4   125.1    846.3  .85    1083  25131  148193  353948  509409  601425   41
 FTW   FORT WORTH         TX    812.1    5.9      .0    818.0  .99     600  23718   89807  170734  316928  466121   42
 IAH   HOUSTON            TX    228.4    1.4   582.4    812.2  .28    7200   2598    8602   34816   79231  169345   43
 ICT   WICHITA            KS    674.9    3.5   124.0    802.4  .84    2879   2194   48806  122611  228142  302256   44
 MSP   MINNEAPOLIS        MN    324.9   20.6   449.0    794.5  .40    2930  25760  178738  453925  739875 1016898   45
 FAI   FAIRBANKS          AK    739.7    2.7    37.1    779.5  .94       0  30618   30618   30618   39715   39715   46
 FAT   FRESNO             CA    645.6   53.9    77.7    777.2  .83    1800  18761  132944  228938  271703  298782   47
 SLC   SALT LAKE CITY     UT    465.8   33.9   268.4    768.1  .60    2787      0   40353  110924  259344  363120   48
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Figure B-3. SAMPLE LISTING OF THE POPULATION DISTRIBUTION AROUND U. S. AIRPORTS; DATA PROVIDED BY THE OFFICE OF ENVIRONMENT AND ENERGY OF THE FAA

Table B-7. Population Density Values By Airport Type and By Distance From Airport, Based on Data Provided by the Office of Environment and Energy of the FAA

Tower Status & Airport Type(s)	Volume Category	Population Density As a Function of Distance From the Airport, People Per Square Mile							
								Average	
		Number of Airports Considered	0-2[1] Miles	2-4 Miles	4-6 Miles	6-8 Miles	8-10 Miles	0-5[1] Miles	0-10[1] Miles
Towered, (General Aviation & Air Taxi)	LOW	62	813	900	701	446	286	830	507
	MEDIUM	82	1807	1817	1557	1244	947	1742	1289
	HIGH	44	2817	2415	2231	2245	2063	2428	2217
Towered, (Air Carrier)	LOW	89	556	495	411	288	206	482	318
	MEDIUM	73	1410	1330	1076	867	692	1268	918
	HIGH	41	3354	3739	3711	3030	2289	3686	2991
Non-Towered, Paved Runways - Lighted &, Unlighted,	LOW	96	323	226	142	135	105	220	144
	MEDIUM	136	340	301	164	96	58	269	129
	HIGH	74	1040	1316	1169	1030	860	1243	860
Non-Towered, Unpaved Runways - Lighted & Unlighted,	AVERAGE	55	516	497	475	368	329	494	396

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[1] Airport land area not included in calculation

A knowledge of two impact parameters is required in order to perform an assessment of community noise impact resulting from aircraft operations: 1) the area exposed to a given noise exposure level and, 2) the number of people within the noise exposed area. A more meaningful impact assessment can be performed if the ambient (or background) noise levels are also considered. The following sections present a detailed descriptgion of the procedures used to determine the required impact parameters and the estimated number of GA airport community residents impacted by GA aircraft noise.

B.5.1 Area Around GA Airports Impacted by GA Aircraft Noise

Galloway[13] has developed a model to relate noise exposed area surrounded by a specified NEF (or L_{dn}) and the number of daily propeller-driven aircraft operations. The relationship is given as:

$$A = 10^{(10 \log_{10} N - NEF - 5.92)/8} \tag{B-1}$$

or

$$A = 10^{(10 \log_{10} N - L_{dn} + 29.08)/8} \tag{B-2}$$

where A is area in square miles.

Equation B-2 is derived from the approximate relationship between NEF and L_{dn} given as:[12]

$$L_{dn} \doteq NEF + 35 \tag{B-3}$$

For airports with GA jet aircraft operations it is assumed that each jet aircraft operation is comparable in noise impact to approximately 200 propeller-driven aircraft.[13]

Based on the data presented on Tables B-5 and B-6, a distribution of the average number of daily GA aircraft operations, by aircraft type, was determined for the towered and non-towered GA airports only (GA airports as defined in Section B.2). The distribution of GA aircraft, along with the "effective" number of daily operations are shown on Table B-8. The effective number of daily operations is the value N used in equations B-1 and B-2 and is determined by counting one jet aircraft operation as 200 propeller-driven aircraft operations, and summing the number of daily GA aircraft operations.

Using equation B-2 and solving for L_{dn} as a function of surrounding area and effective number of daily operations, the expected L_{dn} value at the boundary of each of the GA airports was determined. The average airport areas used to determine the airport boundary noise levels were derived from data supplied the Office of Environment and Energy of the FAA (see Figure B-3). For each GA airport type, two boundary noise levels were computed: 1) noise exposure from GA aircraft operations only and, 2) noise exposure from GA aircraft operations plus the ambient noise. The ambient noise level for each GA airport type was computed from empirical relationships defined in the EPA "100 Site Study"[14] relating day/night ambient noise level and residential population density.* Table B-9 presents a summary of the airport boundary noise level values and the data used to calculate these values. It may be seen from Table B-9 that, even with the addition of the ambient noise to the noise level generated by GA aircraft operations, only the towered GA airports are expected to have boundary noise levels which exceed L_{dn} of 55 dB.

B.5.2 Estimated Area and Number of People Around GA Airports Exposed to L_{dn} Values of 55 dB or Greater

Using equation B-2 and the effective number of daily GA aircraft operations presented on Table B-8, the estimated area and number of people exposed to L_{dn} values 55 dB or greater were calculated for towered and non-towered GA airport types. These estimates are shown on Table B-10. Estimates were determined for two noise exposure conditions: 1) noise

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*Population density values used to compute L_{dn} values were based on total circular area (minus airport area) and total population within a 5-mile radius of the airport.

Table B-8. Distribution of the Average Number of Daily Operations by GA Aircraft and GA Airport Type, Derived from Data Presented on Tables B-5 and B-6

Tower Status and Airport Type(s)	Volume Category	Average Number of Daily Operations			Effective Number of Daily Operations,* N
		Propeller-Driven	Turbojet/Turbofan	Helicopter	
Towered (GA plus AT)	Low	156	3	3	759
	Medium	379	6	11	1590
	High	744	10	12	2756
Non-Towered, Paved Runways - Lighted and Unlighted	Average	105	0.5	2	201
Non-Towered, Unpaved Runways - Lighted and Unlighted	Average	44	0	1	45

*One jet operation counted as 200 propeller-driven aircraft operations; One helicopter operation counted as one propeller-driven aircraft operation.

Table B-9. GA Airport Boundary Parameters: Average Airport Area, Ambient Noise Level and Airport Boundary Noise Level Resulting from GA Aircraft Operations. (Based on CY 1975 GA Operations Data).

Tower Status and Airport Type(s)	Volume Category	Average Airport Area, Sq. Mi.	Ambient Day-Night Sound Level,* dB	Day-Night Sound Level at Airport Boundary, dB	
				GA Aircraft Noise Only	GA Aircraft Noise Plus Ambient Noise
Towered (GA plus AT)	Low	1.74	53.1	56.0	57.9
	Medium	1.32	55.9	60.1	61.5
	High	1.64	57.1	61.8	63.2
Non-Towered, Paved Runways - Lighted and Unlighted	Average	1.05	51.1	52.0	54.7
Non-Towered, Unpaved Runways - Lighted and Unlighted	Average	0.21	51.2	51.0	54.3

*Ambient day-night sound level calculated from average population density computed from the total circular area (minus airport area) and total population within a 5-mile radius of the airport.

Table B-10. Estimated Area and Number of People Around GA Airports Exposed to L_{dn} Values of 55 dB or Greater (Based on CY 1975 GA Operations Data).

Tower Status and Airport Type(s)	Volume Category	Number of Airports	Area Exposed to L_{dn} Values of 55 dB or Greater, Sq. Mi. (minus Airport Area): GA aircraft Noise Only	Area Exposed to L_{dn} Values of 55 dB or Greater, Sq. Mi. (minus Airport Area): GA Aircraft Noise Plus Ambient Noise	Number of People Exposed to L_{dn} Values of 55 dB o rGreater,4/: GA Aircraft Noise Only	Number of People Exposed to L_{dn} Values of 55 dB o rGreater,4/: GA Aircraft Noise Plus Ambient Noise
Towered 1/ (GA plus AT)	Low	69	0.55	6.84	31,499	391,727
	Medium	84	4.46	23.04 2/	652,623	3,371,397
	High	45	9.85	37.19 2/	1,076,211	4,063,379
Non-Towered, Paved Runways - Lighted and Unlighted	Average	3087	3/	3/	-0-	-0-
Non-Towered, Unpaved Runways - Lighted and Unlighted	Average	2475	3/	3/	-0-	-0-

1/ 198 FAA towered airports only.
2/ Ambient day-night sound level greater than 55 dB; area and number of people shown represent area exposed to L_{dn} values equal to ambient noise level plus one dB.
3/ Area exposed to L_{dn} values of 55 dB or greater is within airport boundary.
4/ Number of people exposed is equal to the noise exposed area times the average population density computed from the total circular area (minus airport area) and total population within a 5-mile radius of the airport.

exposure from GA aircraft operations only and, 2) noise exposure from GA aircraft operations plus the ambient noise. From the data presented on Table B-10, it may be seen that only the areas around towered GA airports are, on the average, exposed to L_{dn} values of 55 dB or greater. For these airports, it is estimated that for CY 1975 GA operations, approximately 8 million people were impacted by GA aircraft noise. However, due to the projected increases in GA aircraft operations, the data shown on Table B-10 probably underestimate the current impact from GA aircraft noise.

B.6 REFERENCES

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